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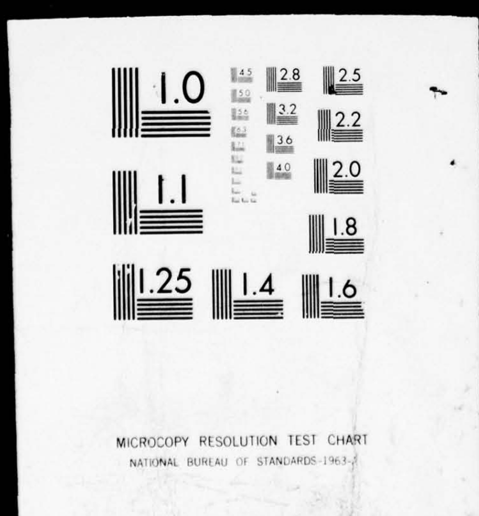

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DURABILITY AND BEHAVIOR OF PRESTRESSED CONCRETE BEAMS

Report 4

POSTTENSIONED CONCRETE BEAM INVESTIGATION WITH LABORATORY TESTS FROM JUNE 1961 TO SEPTEMBER 1975

by

Edward F. O'Neil

Concrete Laboratory
U. S. Army Engineer Waterways Experiment Station
P. O. Box 631, Vicksburg, Miss. 39180

February 1977

Report 4 of a Series

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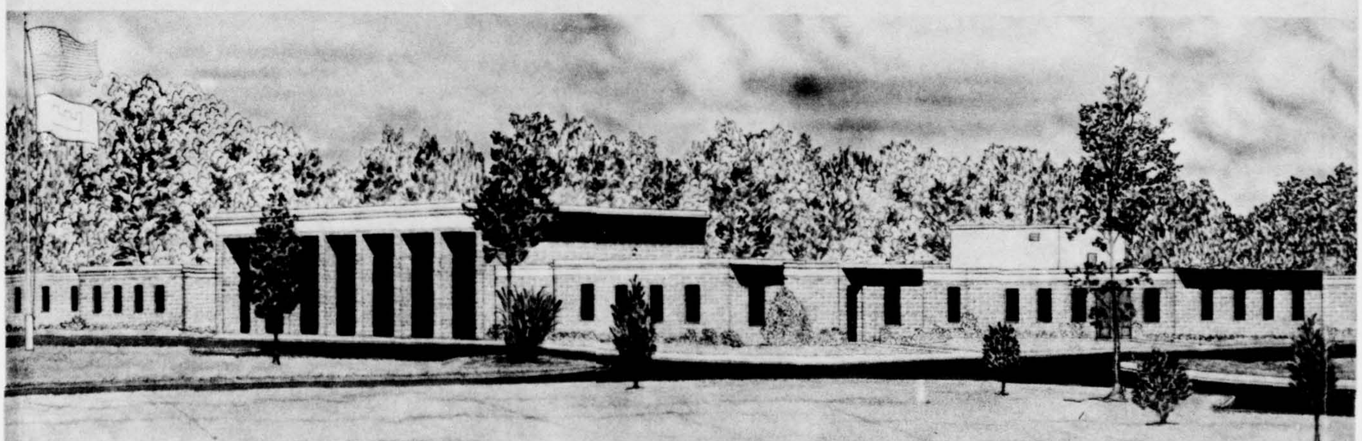

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This report is the fourth in a series describing a study which is being conducted to develop information on the durability of prestressed concrete beams. If no further testing is done to the remaining 12 beams left at Treat Island, Maine, this will be the final report of the posttensioning concrete investigation.

Twenty posttensioned concrete beams were cast between 23 September 1960

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and 3 March 1961 and installed at the Treat Island exposure station in June 1961. The beams were cast around four different types of posttensioning systems, with the posttensioning reinforcement cast at four different eccentricities. Twelve different types of end anchorage protection were cast over external and flush anchorages. The end anchorage protection was attached to the beam with four different types of joint preparation.

The beams were subjected to tidal inundations (wetting and drying) two times each day and also to an average of 131 cycles of freezing and thawing per winter for a test period of 12 to 13 winters.

During the fall of 1973, five beams were returned to the U. S. Army Engineer Waterways Experiment Station for autopsy and testing. Three additional beams were returned during the fall of 1974 for the same purpose. The testing included: (a) structural testing, visual evaluation of the condition, and dissection of the concrete beams; (b) visual evaluation of the end anchorages and the posttensioning conduit; (c) autopsy of the posttensioning system; (d) structural testing of the posttensioning strands; (e) analysis of the products of corrosion on the steel strands; and (f) analysis of the concrete and grout of the beams.

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SUMMARY

This report is the fourth in a series describing a study which is being conducted to develop information on the durability of prestressed concrete beams. This phase of the series is concerned with field and laboratory testing, and observation of end anchorages and end anchorage protection to posttensioned beams. Providing no further testing is to be done to the 12 posttensioned beams that remain at Treat Island, Maine, this report will be the final report of the posttensioning investigation.

Twenty air-entrained, posttensioned beams were fabricated in the summer of 1960 and spring of 1961. Four different types of posttensioning systems were cast at four different eccentricities in the beams. The beams had either external or flush type end anchorages and were protected by either end caps or end plugs. There were four methods of bonding the protective caps and plugs to the beams: bush-hammering, epoxy adhesive, retarding agent, and no protection. The end protections were made from three different mixtures: portland cement concrete, epoxy concrete, and sand-cement mortar.

The beams were installed at the Treat Island exposure station in June 1961 where they underwent field exposure of twice daily tidal inundations and an average of 131 cycles of freezing and thawing each winter for 12 to 13 years. Annual inspection tours were made to Treat Island for testing and inspection of the beams. During these inspection tours, the beams were rated by a panel of observers to determine the condition of the end anchorage protections.

After five years of exposure, an interim report was published, "Durability and Behavior of Prestressed Concrete Beams, Report 2, Posttensioned Concrete Investigation Progress to July 1966." At the conclusion of 12 years of exposure, five beams were returned to the U. S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Mississippi, for autopsy and testing. The testing included: (a) structural testing, visual evaluation of the condition, and dissection of the concrete beams; (b) visual evaluation of the end anchorages and

posttensioning conduit; (c) autopsy of the posttensioning systems; (d) structural testing of the posttensioning strands; (e) analysis of the products of corrosion on the steel strands; and (f) analysis of the concrete and grout of the beams. As a result of this testing, three additional beams were returned to the WES at the end of 13 years of exposure for similar testing and evaluation.

PREFACE

This investigation forms a part of Engineering Study 031 (formerly Civil Works Investigation Item CW 031) and was authorized by multiple letter dated 11 December 1956 from the Office, Chief of Engineers (OCE), U. S. Army. The project plan, "Durability and Behavior of Prestressed Concrete Beams," was drafted in accordance with instructions from OCE and recommendations of the Reinforced Concrete Research Council of the American Society of Civil Engineers.

The test program was carried out by the Concrete Laboratory of the U. S. Army Engineer Waterways Experiment Station (WES), under the direction and supervision of Messrs. Bryant Mather, Chief of the Concrete Laboratory; J. M. Polatty and J. M. Scanlon, Jr., former Chief and Chief, respectively, of the Engineering Mechanics Division; and J. E. McDonald, Chief of the Structures Branch. The project leader was Mr. E. F. O'Neil, who also prepared this report.

Directors of the WES during the conduct of this investigation and the preparation and publication of this report were COL A. P. Rollins, Jr., CE, COL E. H. Lang, CE, COL A. G. Sutton, Jr., CE, COL J. R. Oswalt, Jr., CE, COL L. A. Brown, CE, BG E. D. Peixotto, CE, COL G. H. Hilt, CE, and COL J. L. Cannon, CE. Technical Directors were Messrs. J. B. Tiffany and F. R. Brown.

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CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) AND METRIC (SI) TO U. S. CUSTOMARY UNITS OF MEASUREMENT

Units of measurement used in this report can be converted as follows:

Multiply	By	To Obtain
U. S. Customary to Metric (SI)		
inches	25.4	millimetres
feet	0.3048	metres
square inches	6.4516	square centimetres
cubic yards	0.7645549	cubic metres
gallons (U. S. liquid)	0.003785412	cubic metres
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
pounds (force)	4.448222	newtons
kips (force)	4.448222	kilonewtons
tons (force)	8.896444	kilonewtons
pounds (force) per square inch	0.006894757	megapascals
pounds (force) per minute	0.074137	newtons per second
angstroms	0.0001	micrometres
Metric (SI) to U. S. Customary		
cubic centimetres	0.06102376	cubic inches
grams	0.00220462	pounds (mass)
kilograms	2.204622	pounds (mass)
grams per cubic centimetre	0.0361273	pounds (mass) per cubic inch
Celsius degrees or Kelvins	9/5	Fahrenheit degrees*

* To obtain Fahrenheit (F) temperature readings from Celsius (C) readings, use the following formula: $F = 9/5(C) + 32$. To obtain Fahrenheit readings from Kelvins (K), use: $F = 9/5(K - 273.15) + 32$.

DURABILITY AND BEHAVIOR OF PRESTRESSED CONCRETE BEAMS

POSTTENSIONED CONCRETE BEAM INVESTIGATION WITH LABORATORY TESTS FROM JUNE 1961 TO SEPTEMBER 1975

PART I: INTRODUCTION

Background

1. This project was begun in 1956 to study the durability and behavior of a series of prestressed concrete beams. Twenty posttensioned concrete beams were cast between 23 September 1960 and 3 March 1961 and placed at half-tide elevation at the Treat Island, Maine, exposure station (Figure 1) in June 1961. The beams were subjected to twice daily tidal inundations plus freezing in air and thawing in seawater for 12 to 13 winters. The twenty air-entrained concrete beams were rectangular at the ends (10- by 16-in.* cross section) and were 96 in. long with a 68-in.-long thin web section (5- by 6-in. cross

Figure 1. Concrete beams at Treat Island, Maine, exposure station

* A table of factors for converting U. S. customary units of measurement to metric (SI) units and metric (SI) units to U. S. customary units is presented on page 7.

section). Nineteen of the beams contained posttensioning systems surrounded by a flexible metal conduit (1-1/4- to 1-5/8-in. OD). The other beam contained one unbonded, coated posttensioning tendon that was spiral-wrapped with paper. All beams contained other steel reinforcing that was provided with a nominal 3/4-in. concrete cover. The eccentricity of the unbonded tendon or the metal tubing to enclose the posttensioning tendon was either 0, 1, 2, or 3 in. The other reinforcing was longitudinal steel, stirrups, and bearing grillages. Tables 1-4 present the physical properties of the beams and end protective systems. While References 1 and 2 describe the investigation of pretensioned beams of this study, a detailed description of the interim activities can be found in Reference 3.

Purpose of Investigation

2. The purpose of this phase of the investigation was to test and evaluate prestressed concrete beams and various types of end anchorage protection exposed to long-term weathering. This was accomplished through observation, structural testing, and physical and chemical analyses of eight posttensioned beams determined to be representative of the performances of the prestressing steel and anchorage systems subjected to adverse conditions. Initially five beams were returned to the U. S. Army Engineer Waterways Experiment Station (WES) in September 1973 for testing, with three additional beams being returned in December 1974 for similar tests.

Scope of Investigation

3. The laboratory tests consisted of the following procedures:

- a. An initial photographic inspection.
- b. Destructive testing of each beam to determine the short-term stress-deflection history at 12 to 13 years, the load at initial cracking, the crack pattern history, the ultimate flexural load, and the type of beam failure.
- c. Observation of the corrosion on the conventional

reinforcement and an external inspection of the posttensioning tendons to determine the corrosion present on the end anchorages.

d. An internal photographic inspection of the conduit to determine the details of the grout-steel bond characteristics, corrosion deposited on the grout, grout crack patterns, and corrosion of the steel tendons and the metal conduit.

4. The steel strands and grout of each beam were analyzed to determine the stress-strain relationship and the ultimate strength of the strands and the chemical nature of the corrosion on the steel and in the grout.

Testing Procedure

5. Tables 1-4 relate mixtures used to fabricate posttensioned beams, general information about the posttensioned beams, posttensioning systems used, and twelve types of end anchorage protection used, respectively. Appendix B presents in graphic form the composition of each beam tested and its type of failure under third-point loading.

6. After the beams were received by the Concrete Laboratory at the WES, they were photographed from the landward and seaward ends and from both sides to record any rust areas present on the surfaces and any portions of the beams from which the concrete or the epoxy-concrete caps had spalled or separated, thereby exposing either conventional reinforcement, posttensioning steel, or end anchorage plates.

7. After photographing, the beams were marked at third-point intervals for loading into the testing frame. The 8-ft-long beams had 7.0-ft-long testing spans, and the support markings were placed 6 in. from each end of each beam proper. The protective end caps were not included in the testing length. Where the loading or supporting points occurred in an area in which the concrete had spalled, an epoxy patch was used to repair the area to assure adequate bearing surface during testing.

8. The distance between roller supports was measured on both sides of the beam to ensure that the prescribed testing span was

obtained. The longitudinal orientation of the beam in the frame was checked to avoid longitudinal eccentricities of load. A 60-ton hydraulic ram was used to apply the load to the beam. A ball and socket swivel was placed between the ram and the load-distributing beam to apply the load perpendicular to the test beam. A dial gage with least reading of 0.001 in. was anchored to the frame and centered on the bottom face of the beam to record the center-line deflection. An overall photograph of this apparatus setup is shown in Figure 2.

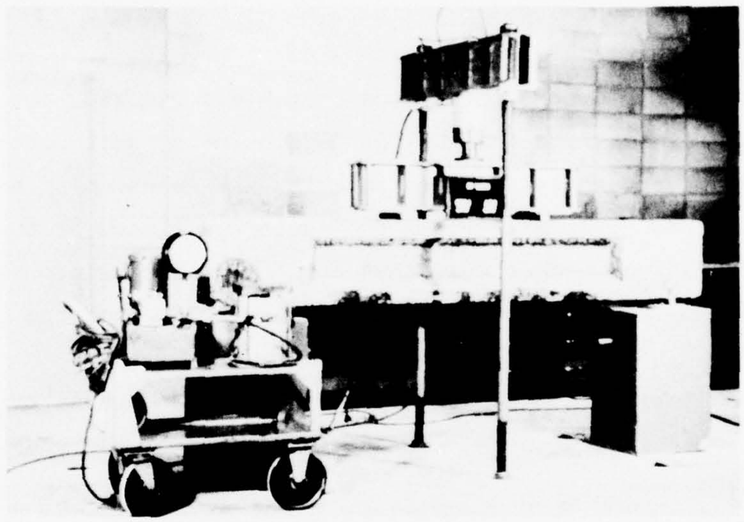


Figure 2. Test apparatus

Loading

9. Each beam was loaded at a constant rate of approximately 2023 lb per min. with dial gage readings taken at each 5000-lb increment. Dial gage readings were recorded to the thousandth of an inch along with the load, ram pressure, and elapsed time. When initial cracking occurred, the cracks were marked, the load was recorded, and a photograph of the crack was taken (see Appendix A, Plates A1-A4, for load-deflection curves).

10. Subsequent to initial cracking, the cracks were marked to record their progress through the beam, and photographs were taken at intermittent load levels throughout the structural testing (see Appendix A , Photos A1-A14).

11. Loading was continued until the beam failed. Observations were made to determine the type of failure, whether the concrete in the compression flange was crushed, if the tendon failed, or if there was a bond failure.

12. When the beam had failed, it was removed from the test frame, the concrete was chipped from the posttensioning tendon, and the conventional reinforcement was removed by means of an air hammer. During this process, care was taken not to injure the conduit surrounding the posttensioned strands.

Examination of the reinforcement

13. When the concrete had been completely removed, the conventional reinforcement cage and the posttensioning conduit were photographed. Records were made of the severity and location of any rust or corrosion present on either the end anchorage plates or the exterior of the conduit. The conduit was then cut out of the reinforcing cage without injuring the conduit, and further examination of the conduit was begun.

14. Following removal of the conduit, it was opened by use of an epoxy abrasive grinding wheel. Repetitive passes of the edge of the grinding wheel were used to ensure that the grout below the conduit was not gouged and its appearance destroyed.

15. Gouging the grout was unavoidable to a certain degree. In order to completely cut through the conduit, a small groove 5/32 in. wide and 3/32 in. long was worn into the surface of the grout. This did not destroy the appearance of the grout but did initiate a crack in the grout coincident with the groove due to concentration of the remaining stresses. In certain areas of the conduit, the grout cover over the posttensioning strands was so thin that the steel below the grout was scratched when the grinding disk cut through both the conduit and the thin layer of grout. The grout cracked when the conduit was opened due to the release of the confining compressive stresses of the conduit.

16. The conduit was then pried back, exposing the grout, and photographs were taken to record any rust or air pockets. The cracked

pieces of grout were removed and fitted back together to give an accurate description of the areas of rust, bond characteristics, air voids, grout thickness, and particle shape.

17. Photographs were taken of any unusual conditions, especially the formation of excessive rust, the occurrence of air voids between the grout and the conduit, and the appearance of air bubbles or rust between the steel strands and the grout.

18. Samples of the grout were taken from various areas in the conduit, labeled, and analyzed for chloride content, grout pH, grout density, and water content.

19. After recording the condition of the grout, the remaining pieces were removed from the conduit, and the steel strands were examined for rust. Each individual strand was labeled and the amount of rust on it recorded. The rust was described as light, moderate, or heavy, depending on the amount of surface area covered. The areas of corrosion were recorded by measuring their distances from either the landward or seaward end of the beam. Any products of corrosion other than rust were also located and the amounts recorded.

20. Each strand of the initial five beams was then scraped with a razor-blade-type knife to remove the rust and corrosion products for analysis by X-ray diffraction (XRD). The diameter of the cleaned strand was then measured with a micrometer at 2-in. intervals along the outer 12-in. lengths and at 6-in. intervals for the rest of the strand to locate the minimum cross-sectional area of the strand. From each strand, three 12-in.-long sections were removed for testing. The three sections were subjected to tension testing, and their stress-strain history was recorded. The physical characteristics of each section were noted and recorded previously (see Table 5 for results).

21. It was decided to return three additional beams for testing to determine if drying and storage of the previous five beams had affected the amount of rust detected, and to study the types of end anchorage protection not evaluated in the first five beams.

22. To provide supplemental information to that obtained in the first investigation, the testing procedure followed for the additional

three beams was essentially the same as that for the first five; however, some tests were omitted and some added to obtain new information. It was decided that no new data would be obtained by analyzing the rust from the strands by XRD analysis since these tests did not detect anything out of the ordinary in the initial investigation. Therefore, this test was dropped from the testing procedure. Also, it was desired to test the strands of one beam for their stress-strain history without first subjecting them to any stresses that would accompany destructive testing of the beam. Thus, the strands of beam 1 were tested without destructively testing the concrete beam. The structural testing of the strands in the initial investigation had indicated that the steel strands protected by a grout-filled conduit were not seriously damaged from rust corrosion and that only the strands in the conduit filled with grease were damaged. Since the three beams subsequently returned had grout-filled conduits, only the strands of the beam were tested that had not been destructively tested to determine whether this had any effect on the strength of the strand.

23. Two additional tests were conducted on these three beams. Since in the first investigation there was no record made of the amount of chloride contamination to the concrete of the beams, each of these beams was tested for chloride contamination across its width at the elevation of the posttensioning conduit.

24. The samples taken for determination of chloride content were removed from five sections along the length of the beam. Cross sections were made at each end of the beam where the width of the beam was 10 in., at 24 in. from each end, and at the midspan where the width of the beam was 5 in. At each cross section, samples of approximately 3 to 6 g were taken at intervals of 2 in. in the 10-in.-wide and 0.9 in. in the 5-in.-wide cross sections. These samples were analyzed for chlorides by a silver nitrate titration test described by Berman.[4]

25. To determine the free water content of the grout around the posttensioning strands, three samples of grout (one from each end and one from the middle) were removed from each conduit. The samples were weighed, dried in an oven at 105°C overnight, and then reweighed to

determine moisture loss and percentage of moisture in the grout (Table 6).

26. The remaining tests conducted in the first investigation, i.e., structural testing of the beam, analysis of the grout, pH of the grout, grout density, and analysis of the corrosion on each strand, were all conducted as outlined in paragraphs 6-20.

PART II: OBSERVATIONS AND TEST RESULTS IN THE FIRST LABORATORY INVESTIGATION

27. The observations and tests conducted in this first laboratory investigation were performed on beams 3, 9, 13, 15, and 19. The observations of corrosion in this investigation relate to the outside of the posttensioning conduit, the posttensioning strands, and the posttensioning end anchorage.

28. In evaluating the extent of corrosion existing on the steel and conduit, the procedure described in Reference 3 was used. It is reproduced below for convenience.

Extent of Corrosion	Surface Area of Strand Coated with Corrosion Products, percent
Heavy	80-100
Moderate	30-80
Light	0-30

29. Every strand of steel examined was found to have some amount and type of corrosion. The most significant type was rust. The amount of rust was categorized as light, moderate, or heavy, depending upon what percentage of the total surface area of the strand was covered. The two remaining types of corrosion, pitting and tarnishing, were also categorized as light, moderate, or heavy; however, their severities were calculated as the percentage of the surface area of the strand that remained after the rust had been calculated. For example, if it was found that 65 percent of the surface area was rusted, the rusting term would be moderate; and if 85 percent of the remaining surface area contained rust pits, then the pitting would be considered heavy. The percentage of tarnishing was also calculated in this manner. These two types of corrosion are discussed in the following paragraphs.

30. Pitting is classified as tiny spots or nicks in the surface of the steel strand that contain or have contained particles of rust at one time. These particles either remained in the pits or were dislodged from them when the grout was removed from the strands. In any event, the presence of pitting was an indication of rust or the presence of

rust at some previous time. The degree of rust stains on the inside surface of the grout did not necessarily indicate pitting alone but merely corresponded to the degree of corrosion in areas where the strand was rusted or pitted. The rusted areas of the strand could have been pitted also, but this could not be determined since the rust covered any pitting that might have been beneath it.

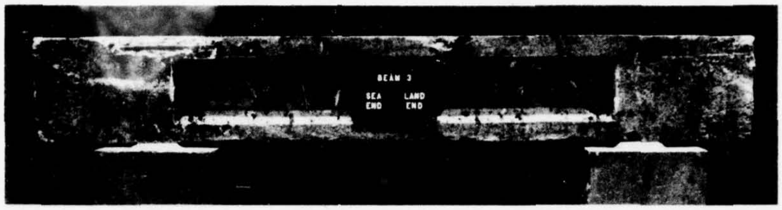
31. Tarnishing is a type of corrosion due to age. Throughout the study, it was observed that the strands had almost entirely lost their new and lustrous appearance, and all the strands were dull to at least a mild degree. Any area that was not rusted or pitted but was dulled through the years by some degree of corrosion was considered tarnished; while this may not be strictly considered rust, it is an alteration of the physical characteristics of the metal by chemical means.

32. It should be pointed out that the system of classification for rust and tarnish may be misleading to some readers. The classifications light and moderate do not present much of a problem because they accurately describe their respective percentages of surface area corroded; however, heavy represents 80-100 percent surface area covered. At 100 percent coverage, the descriptiveness of this system does not tell how badly corroded the steel is but merely states that the surface is fully covered with products of corrosion. The strands in this study that were labeled as heavily corroded did not have deep corrosion and deterioration of the metal, with the exception of the landward end of beam 13. The rest of the strands had not lost more than 0.005 in. in diameter when they were cleaned and sanded. In general, when the classification heavy was used to describe a strand of steel, the percentage of surface area covered was less than or just at 100 percent and corrosion deep in the strand was not present.

Beam 3

33. The as-received condition of beam 3 is shown in Figure 3. Concrete had spalled from the conventional reinforcement in several

a. Side view



b. Side view

c. Landward end view

d. Seaward end view

Figure 3. As-received condition of beam 3

places, exposing the reinforcing bars to attack by seawater. Both of the beam's end protection caps were still attached to the beam and were in good shape. Some of the concrete had spalled from the corners of the landward end protection, but essentially both end caps were intact and in good condition.

34. The landward end of beam 3 was protected by an air-entrained concrete mixture placed over the end of the beam. The end of the beam was prepared by bush hammering. The seaward end was also protected by an air-entrained cap, but the concrete was bonded to a cold joint interface.

35. The strands protruding from the end anchorage of beam 3 were arranged in a circular fashion. For purposes of identification, the strands were numbered as shown in Figure 4 (view from landward end).

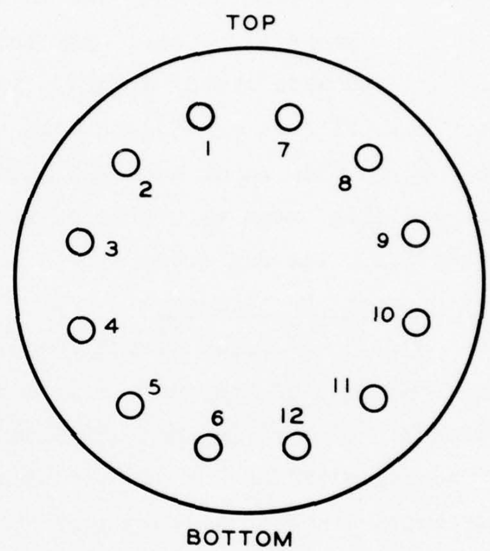


Figure 4. Landward end anchorage, beam 3

Condition of the landward end anchorage

36. The 1-1/4-in. length of each strand that protruded from the end of the anchorage was rusted to varying degrees. Some of the strands were only slightly rusted, while some were corroded to the point that parts of their volumes had been eaten away.

37. Using the nomenclature in Figure 4, the steel strands that protruded from the end of the anchorage were corroded (Photo 1) as follows:

Strand	Volume Missing percent	Strand	Volume Missing percent
1	10	7	85
2	Mild rusting*	8	100
3	Mild rusting*	9	40
4	Mild rusting*	10	Mild rusting*
5	Mild rusting*	11	35
6	10	12	60

* These strands had lost <1 percent of their volumes and were only mildly rusted.

38. The coil of wire that surrounded the concrete of the anchor was relatively free of rust due to the fact that it was buried well within the protective cap. Only the two turns of steel closest to the landward end were rusted at all. The first turn was covered with a heavy coat of rust on its surface, and the second was moderately rusted. The rust on the second turn was mainly at the bottom of the anchorage. The remaining turns were free of rust, and the sand-cement mortar within the coils was dense and solid.

Condition of the conduit

39. The outside of the conduit was only lightly rusted, with less than 1 percent of the surface area coated with rust. Most of this corrosion was located on the underside of the conduit. The corrosion was not concentrated at any one location on the conduit, but the middle and landward portions of conduit had more rust than did the seaward end.

40. Over the entire length of the conduit, the metal seemed to be divided into alternate and irregular areas in which either the metal was smooth and shiny or the surface was textured and dull. These alternating areas were not ordered in length and did not have any pattern. The dull areas greatly outnumbered the shiny ones, and in all cases, the rust appeared on the lustrous portions.

41. There were two small holes on the conduit where the rusting had eaten through the metal. They were both on the landward end and on the side of the conduit. The holes were each about 1/16 in. in diameter, and the heavy rusting around each hole was about 1/8 in. in radius.

42. The inside of the conduit was also only lightly rusted. The corrosion was heavier at the landward than at the seaward end, but still

it never covered greater than 5 percent of the surface area. The rust on the inside was concentrated at the bottom of the conduit, producing rust spots and rust in the valleys of the joints of metal. At the top of the landward end of the conduit were two spots where there was a length of rusting that was due to contact between the steel strands and the conduit. At this point, there appears to have been no grout cover over the steel strands.

43. After the conduit had been sawn through and was being pried open, two of the strands pushed their way through the cut in the conduit. These strands (strands 1 and 2 described in the following paragraphs) protruded from the conduit for approximately 18 in. and at their highest point were 2 in. above the top of the conduit. This observation showed that although the tendon was out of the beam, there was still some stress in the strands. As the conduit was further opened, the grout cracked into pieces due to the release of the radial constraint of the conduit.

44. The following subparagraphs describe the condition of each strand in beam 3.

a. Strand 1.

(1) Landward end: Continuous corrosion existed over the entire end (0-2 in. = light rusting and moderate pitting on the remaining surface; 2-32 in. = moderate rusting and heavy pitting).

(2) Seaward end: Continuous corrosion existed over the entire end (0-18 in. = moderate rusting and heavy pitting; 18-32 in. = heavy rusting and pitting, with some grout remaining well bonded to the steel in this area).

(3) Midsection: Continuous corrosion existed over the entire section (32-57 in. from the landward end = moderate rusting and pitting; 32-39 in. from the seaward end = heavy rusting and pitting).

b. Strand 2.

(1) Landward end: Continuous corrosion existed over the entire end (0-2 in. = moderate rusting and heavy pitting with light patches of bonded grout; 2-32 in. = moderate rusting, mainly where there was bar-to-bar contact, and heavy pitting).

(2) Seaward end: Continuous corrosion existed over the

entire end (0-12 in. = moderate rusting, heavy pitting, and bonded grout; 12-32 in. = moderate rusting and heavy pitting).

(3) Midsection: Continuous corrosion existed over the entire section (32-48 in. from the landward end = moderate rusting and heavy pitting; 32-48 in. from the seaward end = moderate rusting and pitting, with light grout bonded to pitted areas).

c. Strand 3.

(1) Landward end: Continuous corrosion existed over the entire end (0-8 in. = light rusting, mainly where there was bar-to-bar contact, and heavy pitting with light amounts of bonded grout; 8-27 in. = moderate rusting and heavy pitting; 27-32 in. = heavy rusting and pitting, with light grout bonded to the steel).

(2) Seaward end: Continuous corrosion existed over the entire end (0-32 in. = moderate rusting, which was heavier toward the center, heavy pitting, and moderate bonded grout near the end).

(3) Midsection: Continuous corrosion existed over this section (32-39 in. from the landward end = heavy rusting and pitting; 39-64 in. from the landward end = moderate rusting and heavy pitting).

d. Strand 4.

(1) Landward end: Continuous corrosion existed over the entire end (0-3 in. = moderate rusting, mainly where there was bar-to-bar contact, and heavy pitting; 3-6 in. = moderate rusting, where the bar came in contact with the conduit, and heavy pitting elsewhere; 6-25 in. = light to moderate rusting and heavy pitting; 25-32 in. = moderate rusting and heavy pitting, with spots of grout bonded to the steel).

(2) Seaward end: Continuous corrosion existed over the entire end (0-21 in. = moderate rusting, mostly where there was bar-to-bar contact, and heavy pitting close to the seaward end; 21-24 in. = moderate to heavy rusting and heavy pitting, with the strand in this area moderately covered with bonded grout; 24-32 in. = heavy (100 percent) rusting).

(3) Midsection: Continuous corrosion existed in this section (32-42 in. from the landward end = moderate rusting and heavy pitting, with spots of bonded grout; 32-54 in. from the seaward end = heavy rusting).

e. Strand 5.

(1) Landward end: Continuous corrosion existed over the

entire end (0-2 in. = light rusting and heavy pitting; 2-32 in. = moderate rusting, particularly where there was bar-to-bar contact, and moderate pitting). At this end of this strand, the corrosion increased with distance from the end of the strand.

(2) Seaward end: Continuous corrosion existed over the entire end (0-24 in. = moderate rusting and heavy pitting, with grout bonded to the strand from 6 to 18 in.; 24-32 in. = heavy rusting and pitting).

(3) Midsection: Continuous corrosion existed over the entire section (32-48 in. from the landward end = moderate rusting, where there was bar-to-bar contact, and heavy pitting; 32-48 in. from the seaward end = heavy rusting and pitting).

f. Strand 6.

(1) Landward end: Continuous corrosion existed over the entire end (0-2 in. = light rusting and heavy pitting; 2-21 in. = light to moderate rusting and heavy pitting; 21-32 in. = moderate rusting caused mainly by bar-to-bar contact, heavy pitting, and moderate bonded grout cover).

(2) Seaward end: Continuous corrosion existed over the entire end (0-18 in. = moderate rusting and heavy pitting, with moderate grout bonded to the rod; 18-32 in. = moderate rusting and heavy pitting).

(3) Midsection: Continuous corrosion existed over the entire section (32-61 in. from the landward end = moderate rusting, particularly where there was bar-to-bar contact, and heavy pitting, with moderate bonded grout; 32-35 in. from the seaward end = moderate rusting and heavy pitting, with light grout cover).

g. Strand 7.

(1) Landward end: Continuous corrosion existed over the entire end (0-2 in. = no rusting and moderate pitting; 2-32 in. = moderate rusting and pitting).

(2) Seaward end: Continuous corrosion existed over the entire end (0-4 in. = light to moderate rusting and moderate pitting; 4-32 in. = moderate rusting and pitting).

(3) Midsection: Continuous corrosion existed over the entire section (32-39 in. from the landward end = moderate rusting and pitting; 32-57 in. from the seaward end = moderate to heavy rusting and moderate pitting).

h. Strand 8.

(1) Landward end: Continuous corrosion existed over the entire end (0-4 in. = very light rusting and heavy pitting; 4-18 in. = moderate rusting and pitting; 18-32 in. = moderate rusting and heavy pitting).

(2) Seaward end: Continuous corrosion existed over the entire end (0-16 in. = heavy (100 percent) rusting consisting of very tiny rust particles; 16-32 in. = rust increasing from light to moderate and moderate pitting).

(3) Midsection: Continuous corrosion existed over the entire section (32-56 in. from the landward end = moderate to heavy rusting and heavy pitting; 32-40 in. from the seaward end = moderate rusting and pitting; grout bonded to the pitted areas at numerous locations in this section).

i. Strand 9.

(1) Landward end: Continuous corrosion existed over the entire end (0-5 in. = light rusting and heavy pitting; 5-27 in. = moderate rusting and pitting; 27-32 in. = heavy rusting and light pitting).

(2) Seaward end: Continuous corrosion existed over the entire end (0-25 in. = heavy rusting and light pitting, with two patches of grout bonded to the bar at 11 and 25 in., respectively, from the seaward end; 25-32 in. = moderate rusting and pitting).

(3) Midsection: Continuous corrosion existed over the entire section (32-43 in. from the landward end = heavy rusting and light pitting; 32-53 in. from the seaward end = moderate rusting and pitting).

j. Strand 10.

(1) Landward end: Continuous corrosion existed over the entire end (0-5 in. = light rusting and heavy pitting; 5-26 in. = moderate rusting and pitting; 26-32 in. = heavy rusting and moderate pitting).

(2) Seaward end: Continuous corrosion existed over the entire end (0-10 in. = moderate rusting and heavy pitting; 10-32 in. = moderate rusting and heavy pitting, with some grout bonded to the strand).

(3) Midsection: Continuous corrosion existed over the entire section (32-42 in. from the landward end = heavy rusting and moderate pitting; 32-54 in. from the seaward end = moderate rusting and heavy pitting).

k. Strand 11.

(1) Landward end: Continuous corrosion existed over the entire end (0-3 in. = light rust on the surface of the bar due to contact with another bar and moderate pitting; 3-23 in. = light to moderate rusting due to bar contact and moderate pitting; 23-32 in. = heavy rusting and pitting).

(2) Seaward end: Continuous corrosion existed over the entire end (0-18 in. = moderate rusting and heavy pitting; 18-32 in. = moderate rusting and pitting).

(3) Midsection: Continuous corrosion existed over the entire section (32-39 in. from the landward end = heavy rusting and pitting; 32-57 in. from the seaward end = moderate rusting and pitting, with some calcium carbonate deposits on the strand at approximately 50 in. from the seaward end).

l. Strand 12.

(1) Landward end: Continuous corrosion existed over the entire end (0-3 in. = moderate rusting and heavy pitting; 3-32 in. = heavy rusting and pitting).

(2) Seaward end: Continuous corrosion existed over the entire end (0-29 in. = heavy rusting and pitting, with heavy coverage of bonded grout; 29-32 in. = heavy rusting and pitting).

(3) Midsection: Continuous corrosion existed over the entire section (32-35 in. from the landward end = heavy rusting and pitting; 35-46 in. from the landward end = moderate rusting and heavy pitting, with moderate bonded grout; 32-50 in. from the seaward end = heavy rusting and pitting).

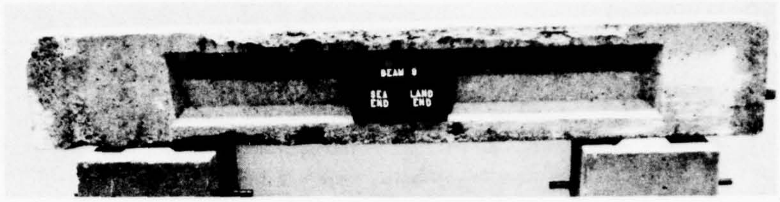
Condition of the seaward end anchorage

45. The 1-1/4 in. of the strands that protruded through the seaward anchorage coil and were embedded in the concrete protective cap were not rusted. Mild pitting was observed on each strand, and all strands were tarnished.

46. The coil of steel around the concrete that made up the end anchorage was likewise free of rust and mildly pitted (Photo 2).

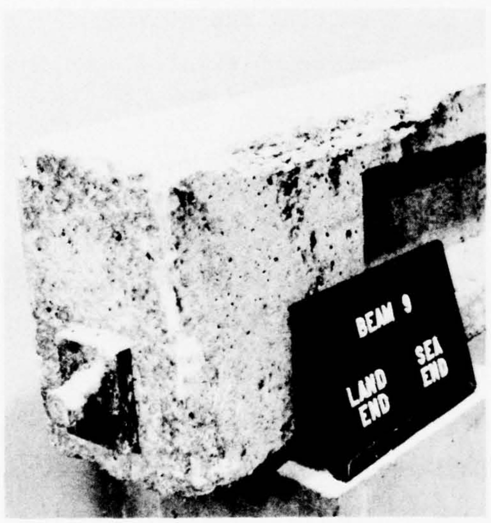
Beam 9

47. The as-received condition of beam 9 is shown in Figure 5.

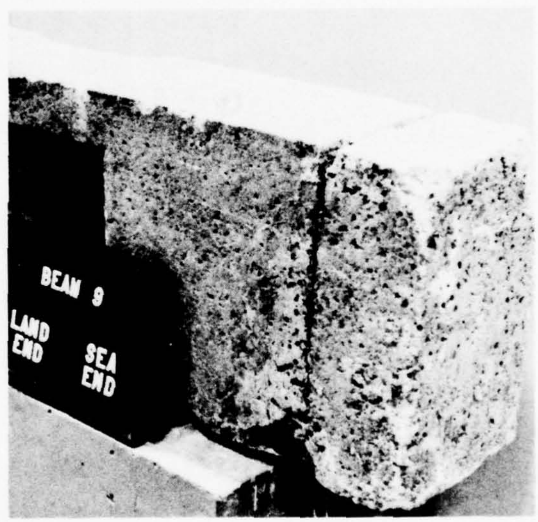


a. Side view

b. Side view



c. Landward end view



d. Seaward end view

Figure 5. As-received condition of beam 9

The concrete cover had spalled from much of the conventional reinforcement exposing it to the corrosive environment. The end anchorage protection cap (Figure 5d) of the seaward end remained intact but was chipped and damaged at the joint. Figure 5c shows the condition of the

landward end. The entire protective cap was missing, and the end anchorage was exposed.

48. The landward end of beam 9 was protected by an air-entrained concrete mixture placed over the end of the beam, which had been prepared by bush hammering. The protective cap for the seaward end was also air-entrained concrete, but it was poured against concrete that contained a retarding agent to slow the time of set and provide a stronger bond between beam and cap.

Condition of the
landward end anchorage

49. The outside of the landward end anchorage plate (Photo 3) was heavily rusted. The entire face of the anchor plate, as well as the threaded end of the posttensioning rod, the washer, and the bolt used to tighten the rod, was corroded. The anchor plate was covered with a thin layer of unsound rusted metal. Parts of this layer had flaked away, and the sound metal below was covered with rust.

50. The four edges of the anchor plate were also covered with rust, which was heavy but not as deep as that on the face of the plate. This anchor was cast with its inside face flush with the landward extremity of the beam so that the edges would be exposed to the same corrosive factors that the face received. As stated in paragraph 47 and shown in Appendix B, this beam was returned to the WES with the landward end protective cap missing. The bolt on the posttensioning rod at this end had some spots where the steel was uncorroded, but the major portion of the steel was covered with rust.

51. The inside face of the end anchorage plate was very mildly rusted. The few patches of rust that were located near the outside edges of the plate were heavily rusted but did not extend inward for more than 1 in. from the edge.

Condition of conduit

52. The outside of the conduit was free from rust between the end anchorages. The landward end funnel had become dull and had concrete stuck to its surface. This was also true of the seaward funnel. When the landward housing was opened, the grout beneath the housing and

outside of the conduit had not penetrated to the full bounds that it could be pumped. As shown in Photo 4, the grout appeared rounded and tapered into the conduit inside, leaving a cavity between the housing and the conduit. When the housing was removed, the grout beneath it was hard and dense and lightly rust-stained on the bottom surface. The housing was rusted on the bottom, but the rust cover was moderate. The length of conduit beneath the funnel housing that was not covered with grout was covered with tiny rust specks and dulled heavily. The seaward end funnel was also dull and covered with a light layer of concrete, but when it was opened, the grout beneath filled the entire cone. The top surface of the grout inside the housing revealed air pockets, and some of the grout around these pockets appeared white, soft, and chalky. The remainder of the grout in the housing was dense and hard. The outside surface of the seaward housing had completely lost its luster and was moderately covered with a layer of grout. The inside of the housing showed a moderate cover of rust, mostly on the bottom of the housing. The remainder of the inside was dull and had a light cover of grout.

53. When the conduit was opened, the grout inside appeared lightly rust-stained. The grout on the bottom side of the conduit was stained more than that at the top; however, it was still considered only light. The rust that appeared on the surface between the grout and the conduit was found mainly in the valleys formed by the joints in the conduit. These valleys appeared as ridges on the grout. Photos 5-8 show the condition of the bottom of the conduit from the landward end through the middle section to the seaward end and the conditions of the pieces of grout associated with each section. The central section (Photo 7) exhibits the greatest amount of rusting on the conduit, and its pieces of grout have the most rust on them. Photo 8 shows the seaward end of the conduit at the funnel housing and an isolated patch of heavy rusting.

54. The grout from this tendon broke into pieces so small that it was not feasible to reassemble the sections of grout. This was a result of the type of posttensioning system used. The stressed bar of this system had a diameter not significantly smaller than that of the conduit such that the thickness of grout between the conduit and the bar

was not very substantial. Also, when the bar was placed inside the conduit and grouted, the longitudinal axis of the posttensioning rod was slightly above that of the conduit throughout the length of the beam. This made the grout cover at the top much thinner than that at the bottom, as reflected by the crack pattern of the grout. At the top, the pieces of grout broke into tiny thin pieces, while at the bottom they were thicker and more elongated (Photo 6). At the surface of the posttensioned bar, the grout was rust-stained to match the surface of the bar. Small pitting-type rust stains appeared on the grout which were similar to the pitting on the bar.

55. The following subparagraphs describe the condition of the bar in beam 9.

a. Landward end: Continuous corrosion existed over the entire end (0-32 in. = light to moderate rusting and moderate pitting and tarnishing, with a thin layer of grout that remained on the bar from 0 to 17 in.).

b. Seaward end: Continuous corrosion existed over the entire end (0-32 in. = moderate rusting and moderate pitting; from 4 to 6 in. from the seaward end, on the bottom of the bar, there was an area 2 in. long and 1/2 in. wide that was very heavily rusted, and from 26 to 29 in., there was an area of moderate to heavy rusting and heavy pitting and tarnishing).

c. Midsection: Continuous corrosion existed over the entire section (32-48 in. from the landward end and 32-48 in. from the seaward end = light rusting, moderate pitting, and moderate tarnishing).

Condition of the seaward end anchorage

56. The outside face of the seaward end anchor plate was heavily corroded. Most of the top layer of unsound rusted metal had been corroded away, leaving the sound steel below heavily rusted. The washers between the bolt and face of the plate were heavily corroded over 50 percent of their exposed surface areas as was the bolt. The remaining areas of these pieces were free of rust but were tarnished.

57. The four edges of this anchorage were tarnished but only mildly rusted. As with the landward end, the rust appeared in heavy patches around all four edges. This same result occurred on the inside

face of the seaward anchorage plate (Photo 9).

Beam 13

58. The as-received condition of beam 13 is shown in Figure 6. Concrete had spalled from the conventional reinforcement at the bottom of the beam. There was one large spalled area at the top of the seaward end of this beam. The concrete caps used as end anchorage protection were only slightly damaged at the corners; otherwise, they were not damaged. Both end anchorage protective caps, at the time they were returned to the WES, had developed cracks between the caps and the actual beam (Figure 6c and d).

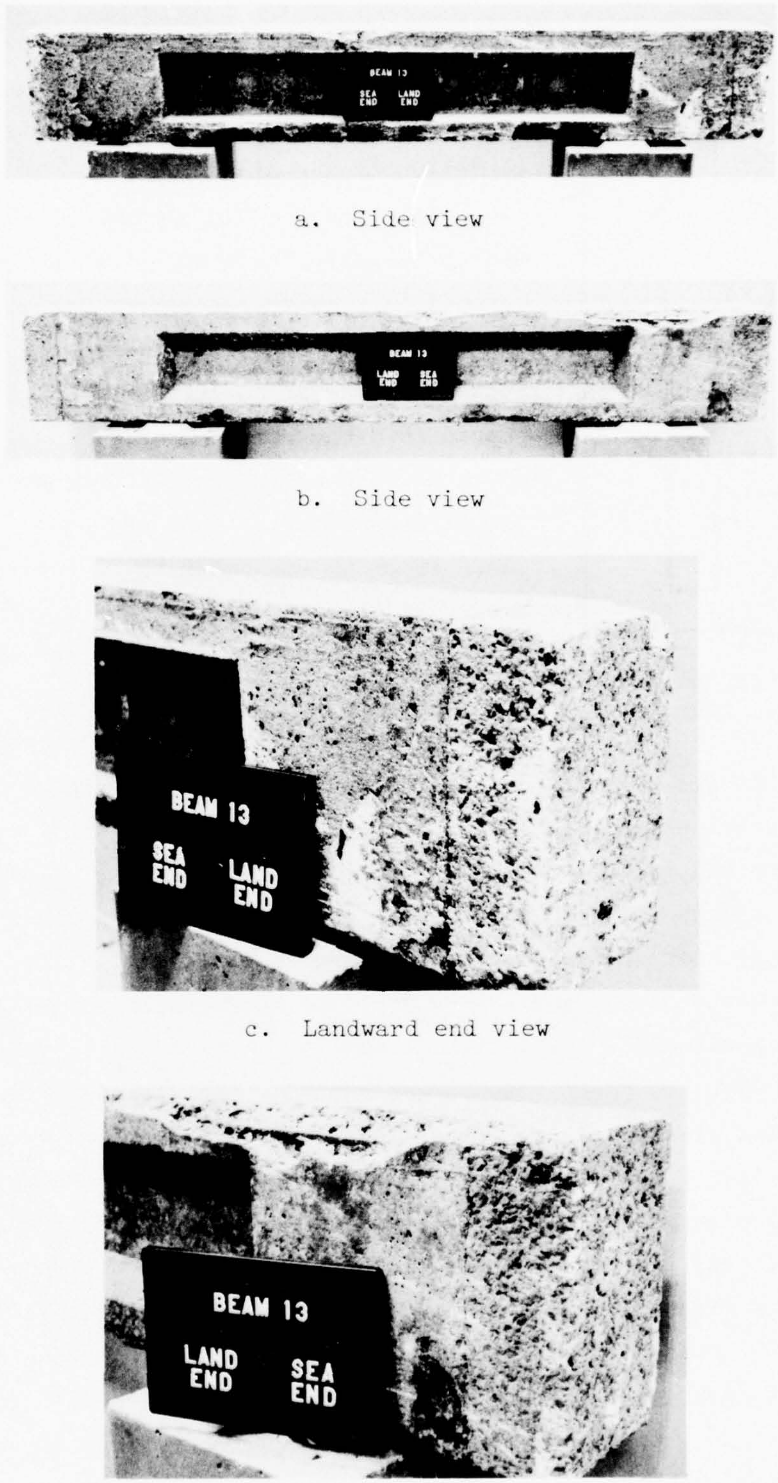
57. The landward end of beam 13 was protected by an air-entrained concrete mixture placed around the anchorage and bonded to the unprepared end of the beam. The seaward end of the beam also received an air-entrained concrete cap; however, the end of the beam was prepared for the cap by bush hammering.

60. The strands of the tendon in beam 13 were arranged as shown in Figure 7. For purposes of identification, they were numbered as shown (view from landward end).

Condition of the landward end anchorage

61. Starting from the landward extremity, the round anchor plate and button ends of each strand were heavily corroded. The grout around the strands had been discolored by the rust (Photo 10). The two metal spacing bars directly behind the round anchor plate were lightly to moderately rusted, and the remaining areas were tarnished. The edges of these bars were more heavily rusted than were the exposed faces. The outside face of the rectangular anchor plate was moderately rusted. In areas of heavy rusting, the metal had flaked, exposing sound steel below. The remainder of this face was moderately pitted and tarnished.

62. The edges of this plate were lightly to moderately rusted (Photo 11). A light amount of grout remained bonded to the metal surface. The inside face of the end anchorage was moderately rusted



a. Side view

b. Side view

c. Landward end view

d. Seaward end view

Figure 6. As-received condition of beam 13

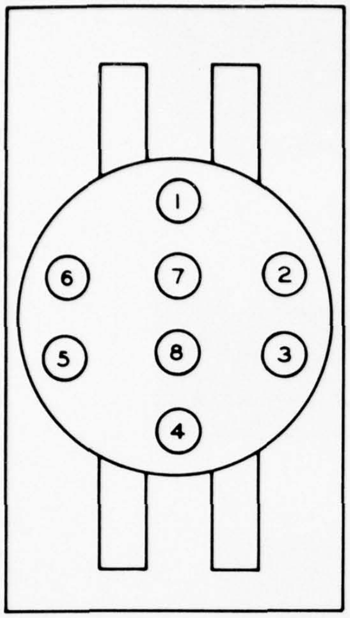


Figure 7. Landward end anchorage, beam 13

with heavy tarnish and pitting. Most of the rusting was concentrated in the area of the plate through which the strands passed.

Condition of the conduit

63. The conduit of beam 13 was not made of metal. The steel strands were wrapped in a heavy paper-type conduit that was several layers deep. These bars were protected against corrosion by grease pumped into the paper conduit.

64. When all the concrete was removed from the reinforcing cage and tendons, the paper wrapping was found to be heavily damaged. In at least five places along the conduit, the paper was torn, with two places exposing grease and the strands (Photo 12). The remainder of the conduit was frayed and tattered. It was determined that the damage to the conduit at the paper tears was not the results of removing the concrete from the conduit because portions of the paper had become thin and brittle with age. At the two spots where the strands were exposed, they were covered with concrete dust that had stuck to the grease in the conduit. For the most part, the bars in these areas were dry, and at least 50 percent of the exposed area was not covered with grease.

65. When the paper conduit was removed, the strands were found to be stained black from the grease that covered them. Photo 13 shows a general view of the strands subsequent to removing the conduit. In some of the areas, the grease still coated the strands and was sticky. In other places, the strands were black but were covered with a dried-out layer of grease or exhibited areas of no grease. The rust was very difficult to locate and distinguish from bits of paper conduit because they both looked alike since both were black and covered with grease. The rust attacked areas where the grease was gone or dried up, and overall there was not enough grease present to fill the paper conduit.

66. The grease was steam-cleaned from the surface of the strands after a preliminary check for rust, and an analysis for corrosion was made. The following subparagraphs describe the condition of each strand in beam 13.

a. Strand 1.

(1) Landward end: Continuous corrosion existed over the entire end (0-8 in. = heavy rusting, light pitting and tarnishing; 8-24 in. = moderate rusting, light pitting and tarnishing; 24-32 in. = light rusting, no pitting or tarnishing).

(2) Seaward end: Continuous corrosion existed over the entire end (0-12 in. = moderate rusting, light pitting and tarnishing; 12-32 in. = light rusting and pitting).

(3) Midsection: This section was corroded in one area (46-50 in. from the landward end = heavy rusting and moderate pitting).

b. Strand 2.

(1) Landward end: Continuous corrosion existed over the entire end (0-4 in. = moderate rusting and tarnishing; 4-22 in. = moderate rusting, light pitting and tarnishing; 22-32 in. = light rusting, pitting, and tarnishing).

(2) Seaward end: Continuous corrosion existed over the entire end (0-4 in. = light rusting, moderate pitting and tarnishing; 4-12 in. = moderate rusting, pitting, and tarnishing; 12-18 in. = light rusting, moderate pitting and tarnishing; 18-32 in. = moderate rusting, pitting, and tarnishing).

(3) Midsection: The entire midsection of this strand was moderately rusted with moderate amounts of pitting and tarnishing.

c. Strand 3.

(1) Landward end: The first 22 in. of this end of the strand was covered with corrosion (0-12 in. = heavy rusting, pitting, and tarnishing; 12-14 in. = moderate rusting, light pitting and tarnishing; 14-22 in. = light rusting, pitting, and tarnishing).

(2) Seaward end: Continuous corrosion existed over the entire end (0-18 in. = moderate rusting, light pitting and tarnishing; 18-32 in. = light rusting and no pitting or tarnishing).

(3) Midsection: The entire midsection of this strand

was moderately rusted with light pitting and tarnishing.

d. Strand 4.

(1) Landward end: Continuous corrosion existed over the entire end (0-8 in. = heavy rusting, pitting, and tarnishing; 8-20 in. = moderate rusting, light pitting and tarnishing; 20-32 in. = light rusting, pitting, and tarnishing).

(2) Seaward end: Continuous corrosion existed over the entire end (0-18 in. = moderate rusting, light pitting and tarnishing; 18-32 in. = light rusting, pitting, and tarnishing).

(3) Midsection: The entire midsection (32 in.) was moderately rusted and lightly pitted and tarnished.

e. Strand 5.

(1) Landward end: Continuous corrosion existed over the entire end (0-4 in. = heavy rusting, pitting, and tarnishing; 4-9 in. = heavy rusting, moderate pitting and tarnishing; 9-32 in. = moderate rusting and none to light pitting and tarnishing).

(2) Seaward end: Continuous corrosion existed over the entire end (0-32 in. = moderate rusting, light pitting and tarnishing).

(3) Midsection: Continuous corrosion existed over the entire section (32-40 in. from the landward end = light rusting, no pitting or tarnishing; 40-52 in. from the landward end = moderate rusting, light pitting and tarnishing; 32-38 in. from the seaward end = light rusting, no pitting or tarnishing; 38-44 in. from the seaward end = moderate rusting, light pitting and tarnishing).

f. Strand 6.

(1) Landward end: Continuous corrosion existed for the first 24 in. of this end (0-8 in. = heavy rusting, light pitting and tarnishing; 8-24 in. = moderate rusting, light pitting and tarnishing).

(2) Seaward end: Continuous corrosion existed over the entire end (0-18 in. = moderate rusting, light pitting and tarnishing; 18-32 in. = light rusting, no pitting or tarnishing).

(3) Midsection: Corrosion was absent from this section with the exception of two areas (42-48 in. from the landward end = moderate rusting, light pitting and tarnishing; 36-44 in. from the seaward end = light rusting, no pitting or tarnishing).

g. Strand 7.

(1) Landward end: Continuous corrosion existed over the entire end (0-3 in. = heavy rusting, pitting, and tarnishing; 3-24 in. = moderate rusting, pitting, and tarnishing; 24-32 in. = light rusting, moderate pitting and tarnishing).

(2) Seaward end: Continuous corrosion existed over the entire end (0-12 in. = light rusting, moderate pitting and tarnishing; 12-32 in. = moderate rusting, pitting, and tarnishing).

(3) Midsection: The entire midsection was moderately rusted, and the rest of the strand had moderate pitting and tarnishing.

h. Strand 8.

(1) Landward end: Continuous corrosion existed over the entire end (0-10 in. = heavy rusting, pitting, and tarnishing; 10-24 in. = moderate rusting, pitting, and tarnishing; 24-32 in. = light rusting and moderate pitting and tarnishing).

(2) Seaward end: Continuous corrosion existed over the entire end (0-32 in. = light rusting and moderate pitting and tarnishing).

(3) Midsection: The entire midsection was lightly rusted and moderately pitted and tarnished.

On all the strands directly inside the landward end, the metal was so badly rusted that the steel was reduced in cross section by a relatively significant amount. One strand was so reduced that it broke about 5/8 in. from the inside face of the end anchorage (Photo 14). The portions of the bar to which the grease had adhered were not rusted, only tarnished, but where the grease had worn off, the bars were pitted and rusted.

Condition of the
seaward end anchorage

67. The round anchorage plate and the ends of the strands were heavily rusted, both on the outside surface and the edges. The two spacer bars were lightly to moderately rusted, with most of the rust occurring on the edges of these plates. The areas on these plates that were not rusted were heavily tarnished and exhibited some pitting (Photos 15 and 16). The ends of the strands that were outside the beam

were moderately rusted and heavily tarnished. The outside face of the rectangular anchorage plate was moderately rusted. There appeared to be heavy pitting and scarring on the remainder of the surface. The edges of this plate were also moderately rusted and heavily tarnished. Inside, the face of this plate was heavily rusted in the vicinity of the holes through which the strands passed (Photo 17), and the pieces of strand were also heavily rusted. On the remainder of this surface, the steel was moderately rusted and tarnished.

Beam 15

68. The as-received condition of beam 15 is shown in Figure 8. Heavy spalling occurred on one side of the beam only and mainly at the top of the beam. The spalling at the top seaward end exposed the conventional reinforcement caging.

69. The landward end of beam 15 was protected by an external air-entrained concrete cap. The concrete of the beam at this end had a set-retarding agent added to aid in the bonding of the protective cap. This end protection (Figure 8c) was intact and had not developed any bond cracks at the time it was received.

70. The seaward end of this beam was protected by an air-entrained concrete cap that was bonded to the main beam by an epoxy adhesive between the beam and protective cap. As shown in Figure 8d, part of this cap broke away from the beam, exposing the end anchorage to the environment.

71. The arrangement of the strands in beam 15 is the same as in beam 13 (Figure 7).

Condition of the landward end anchorage

72. The outside face of the landward end anchorage was heavily rusted. The circular anchorage plate was covered with a heavy coat of finely pitted rust, and the edges of this plate were equally pitted. The rectangular spacer plates were moderately rusted, and the remainder of the plate was heavily pitted and tarnished. The large rectangular

a. Side view

b. Side view

c. Landward end view

d. Seaward end view

Figure 8. As-received condition of beam 15

anchorage plate was moderately rusted on the outside face and also heavily pitted and tarnished. Much of the concrete stuck to this plate, but this did not stop the corrosion. Photos 18 and 19 show how the plate was rusted even where the concrete had been chipped away. The edges of the large bearing plate were lightly rusted but heavily tarnished, and the inside face of the plate had almost no rust but was heavily tarnished.

Condition of the conduit

73. The landward and seaward funnels were opened first. The grout beneath the landward end housing appeared sound. There was a slight amount of rust between the housing and the grout. The grout under the funnel covered the end of the conduit for approximately 4 in. When the grout was removed, this portion of the conduit was heavily rusted with tiny pitting rust spots (Photo 20). Where the funnel ended and the conduit was exposed, the rusting stopped. As more grout was removed from beneath this housing, the rods were observed to be moderately rusted (Photo 21); when the conduit was cut, the strands beneath the rusted portion of the conduit were also rusted. Samples of the grout from this area were collected to be analyzed.

74. When the seaward end housing was opened, it was noted that the grout at the top of the housing was weak and filled with air voids. There was a thin layer about 1/16 in. thick that would break away from the grout beneath it. This layer was of poor quality, indicating a high amount of water present at the time of set. No rust was present on either the inside surface of the housing or the grout. In contrast to the part of the conduit covered by the housing at the landward end, the part covered by the seaward end funnel was bright and lustrous, showing no rust at all (Photo 22).

75. The grout under this housing broke in irregular, elongated pieces. These pieces were long and thin and generally pointed at the ends in contrast to the pieces from the landward end, which were rectangular and thick.

76. The outside of the conduit was moderately rusted. This occurred over the entire length of the beam and appeared in masses of

tiny pinpoint rust spots. The rust was concentrated mainly on the upper half of the conduit but was relatively uniform over the entire length. The only exception to this was the heavily rusted area of the conduit under the landward end funnel.

77. As the conduit was opened, it was noted that the grout toward the seaward end of the beam at the top of the conduit was basically free of rust. There were a few tiny spots of rust, but they were spread out. Photo 23 shows the condition of the grout just after the conduit was opened. This shot of the seaward end shows how the grout cracked longitudinally, relieving the remaining stress in the steel. Photo 24 is a close-up of the grout in this area. The grout at the top of the conduit contained air voids and laitance, indicating an excess of water when the grout was pumped into the conduit. As the conduit was further pried open, the grout broke into small pieces and the strands of steel inside were exposed (Photo 25). This completely relieved any remaining stresses in the steel since the conduit was now draped from end to end, and no longer had the stiffness that was present prior to opening the conduit.

78. Photo 26 shows the grout at the top of the conduit close to the landward end of beam 15. At this point, the strands came closer to the top of the conduit (Photo 27), causing the grout to be somewhat thinner than that at the seaward end. This thinner grout broke into smaller pieces due to the thinness of the layer between the conduit and the strands. The strands in this area had light amounts of rusting.

79. The grout at the center of the beam was somewhat less dense than that at either end, and also the pieces were more elongated at the center than at the ends; consequently, the pieces of grout were weaker in this area.

80. At a spot approximately 18 in. from the seaward end of the beam, some of the grout around the strands changed in appearance. For about 4 in., some of the grout appeared to be covered with a milky white powder. The pieces came from the bottom of the conduit beneath one of the strands of steel. Photo 28 shows the shape and appearance of the affected grout. The cross section of the piece of grout was circular

on the bottom to conform to the outside of the conduit and flat on top, with an indentation where the posttensioning rods touched it. The flat surface was smooth and milky white, and it appeared that this piece had no bond to any other grout surface. There were some smaller pieces of grout in this area that also contained traces of this deposit, but they did not fit together with those shown in the photograph. Chemical analysis of this grout showed the milky white powder to be calcium carbonate.

81. The inside of the conduit was very lightly rusted. At the seaward end of the conduit, no rust spots were on the inside, and the metal was shiny and lustrous. Between the seaward end and the center, the only rust that occurred was at the edges of the spot where the calcium carbonate leached from the grout. This tiny bit of rust amounted to less than 1 percent of the surface area. At the center of the conduit, the metal was lightly rusted. Tiny spots of rust appeared on the conduit and in the joints between the segments. This rust still amounted to less than 1 percent of the surface area. Toward the landward end of the center, there was a 5- to 6-in.-long area in which rust spots appeared on every rib and in every joint. These rust spots possibly accounted for 5 percent of the surface area. At the landward end, the rust again became light and was limited to a few spots. This was true except for the area of the conduit under the landward end housing that was described previously. It was moderately rusted (about 40 percent), with more of the rust occurring on the top half than on the bottom.

82. There seemed to be relatively more rust at the landward end than at any other place on the inside of the conduit. Most of the rust appeared in the joints of the conduit between each rib, but there were incidents of rust spots on the ribs. All the rust was categorized as light except for the moderate area at the landward end.

83. The following subparagraphs describe the condition of each strand in beam 15.

a. Strand 1.

(1) Landward end: Continuous corrosion existed over the

entire end (0-6 in. = moderate rusting and pitting, heavy tarnishing; 6-14 in. = heavy rusting and pitting, moderate tarnishing; 14-32 in. = light rusting and pitting, moderate tarnishing).

(2) Seaward end: Continuous corrosion existed over the entire end (0-32 in. = light rusting and pitting, moderate tarnishing).

(3) Midsection: Continuous corrosion existed over the entire section (light rusting and pitting and moderate tarnishing over the entire section).

b. Strand 2.

(1) Landward end: Continuous corrosion existed over the entire end (0-18 in. = moderate rusting, pitting, and tarnishing; 18-32 in. = light rusting and pitting, moderate tarnishing).

(2) Seaward end: Continuous corrosion existed over the entire end (0-10 in. = moderate rusting, light pitting and tarnishing; 10-32 in. = light rusting and pitting, moderate tarnishing, with some calcium carbonate powder on the strand from 20 to 22 in.).

(3) Midsection: Continuous corrosion existed over the entire section (light rusting and pitting, moderate tarnishing over the entire section).

c. Strand 3.

(1) Landward end: Continuous corrosion existed over the entire end (0-16 in. = moderate rusting, light pitting, and moderate tarnishing; 16-32 in. = light rusting, moderate pitting and tarnishing).

(2) Seaward end: Continuous corrosion existed over the entire end (0-32 in. = light rusting and pitting, moderate tarnishing).

(3) Midsection: Continuous corrosion existed over the entire section (light rusting and pitting and moderate tarnishing throughout the 32 in., with a line of rust where two strands were in contact between 36 and 39 in. from the landward end).

d. Strand 4.

(1) Landward end: Continuous corrosion existed over the entire end (0-8 in. = light rusting and pitting, moderate tarnishing; 8-12 in. = moderate rusting, pitting, and tarnishing; 12-32 in. = light rusting and pitting, moderate tarnishing).

(2) Seaward end: Continuous corrosion existed over the entire end (0-32 in. = light rusting, pitting, and

tarnishing, with moderate amounts of grout stuck to the strand from 0 to 6 in.).

(3) Midsection: Continuous corrosion existed over the entire section (light rusting and pitting, moderate tarnishing over the entire section).

e. Strand 5.

(1) Landward end: Continuous corrosion existed over the entire end (0-6 in. = moderate rusting and pitting, heavy tarnishing; 6-14 in. = heavy rusting and pitting, moderate tarnishing; 14-32 in. = light rusting and pitting, moderate tarnishing).

(2) Seaward end: Continuous corrosion existed over the entire end (0-32 in. = light rusting and pitting, moderate tarnishing).

(3) Midsection: Continuous corrosion existed over the entire section (light rusting and pitting and moderate tarnishing over the entire section, with a line of rust due to strand-to-strand contact from 50 to 56 in. from the landward end).

f. Strand 6.

(1) Landward end: Continuous corrosion existed over the entire end (0-12 in. = moderate rusting, heavy pitting and tarnishing; 12-32 in. = light rusting, moderate pitting and tarnishing).

(2) Seaward end: Continuous corrosion existed over the entire end (0-32 in. = light rusting and pitting, moderate tarnishing).

(3) Midsection: Continuous corrosion existed over the entire section (light rusting and pitting and moderate tarnishing over the entire section).

g. Strand 7.

(1) Landward end: Continuous corrosion existed over the entire end (0-14 in. = moderate rusting and pitting, heavy tarnishing; 14-32 in. = light rusting and pitting, moderate tarnishing).

(2) Seaward end: Continuous corrosion existed over the entire end (0-32 in. = light rusting and pitting, moderate tarnishing).

(3) Midsection: Continuous corrosion existed over the entire section (light rusting and pitting and moderate tarnishing over the entire section).

h. Strand 8.

(1) Landward end: Continuous corrosion existed over the

entire end (0-5 in. = light rusting, heavy pitting and tarnishing, with moderate amounts of grout stuck to the strand; 5-14 in. = moderate rusting and pitting, heavy tarnishing; 14-32 in. = light rusting and pitting, moderate tarnishing).

(2) Seaward end: Continuous corrosion existed over the entire end (0-32 in. = light rusting and pitting, moderate tarnishing).

(3) Midsection: Continuous corrosion existed over the entire section (light rusting, pitting, and tarnishing over the entire section, with a line of rust due to steel-to-steel contact from 51 to 54 in. from the landward end).

Condition of the
seaward end anchorage

84. The outside face of this anchorage was very heavily rusted. The round anchor plate was corroded over its entire surface area. The protective cap broke off before the specimen left the Treat Island exposure station, and the color of the concrete that was left bonded to the rusting steel had changed to the dark brown color of the rust.

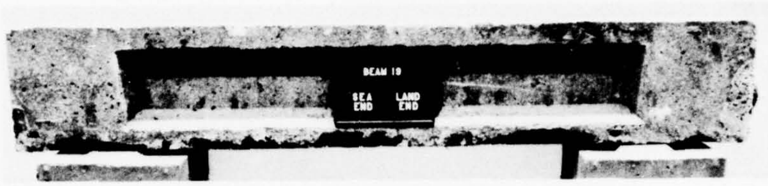
85. The small rectangular plates were heavily rusted but were covered with concrete that bonded to the steel. The rusting had progressed so far in some areas that the rust flakes were 1/32 in. thick and the steel below the flakes was heavily rusted. The edges of the plate were also heavily rusted, but not to such a drastic degree. The inside face of the end anchorage that was buried in the concrete was moderately rusted and heavily tarnished. The tarnished areas were sound, and the rusted areas also pitted (Photos 18 and 19).

Beam 19

86. The as-received condition of beam 19 is shown in Figure 9. Concrete had spalled from only one edge, exposing the conventional reinforcement at two places. The remaining three edges did not have any spalling present.

87. The end anchorage plates on both ends were exposed since the end protection caps were both missing at the time of delivery to the WES.

a. Side view



b. Side view

c. Landward end view

d. Seaward end view

Figure 9. As-received condition of beam 19

The landward end of beam 19 had been protected by an air-entrained concrete mixture placed over the end of the beam; the concrete mixture had a set retarder added to aid in the bonding of the cap. The seaward end had been protected by an air-entrained mixture cast over the beam surface, which had been sandblasted and coated with epoxy to facilitate bonding.

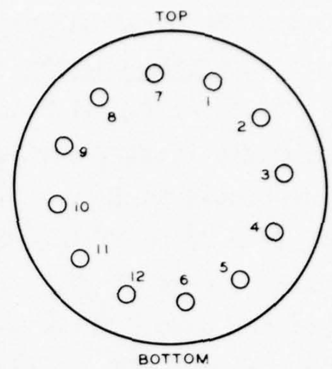


Figure 10. Strand numbering, beam 19

88. The strands of the tendon in beam 19 were arranged in a circular fashion. For purposes of identification, the strands were numbered as shown in Figure 10 (looking from the landward end).

Condition of the
<u>landward end anchorage</u>

89. The outside face of the landward end anchorage plate was directly exposed to seawater attack and was very heavily corroded and rusted. The metal was very deeply rusted in spots; some of the flakes of rusted metal were as thick as 3/16 in. This rusted metal flaked and chipped away from the stronger metal below. Even below the unsound layer, the metal was coated with a heavy layer of rust (Photo 29). The edges of the plate were moderately rusted, and the areas not rusted were heavily tarnished. The rust appeared heavier toward the outside of the edges where the water could have more easily penetrated. The rust was in patches of small specks, and there was no flaking rust.

90. The inside of this end plate (Photo 30) was heavily scarred and tarnished. The overall face of the plate was only slightly rusted, but there were two patches of heavy rusting. In this photograph, the upper right-hand corner was the most heavily rusted, and the lower left-hand corner, hidden by the strands, was similarly rusted. The rusting was confined to the edges of the inside face. The central portion of the end plate near the funnel housing was only tarnished. The funnel housing at the landward end of the beam was not rusted at

all, but the metal was entirely tarnished.

Condition of the conduit

91. The funnel housing at the landward end was not rusted. On the conduit itself, rusting began about 27 in. from the landward face and continued to 32 in. The rusting was heavy from 27 to 29 in. and light from 29 to 32 in. The midsection of the conduit contained small patches of rust at 39, 42, 45, 47, 50, and 61 in. from the landward end of the beam. These patches were moderate in severity. The rusting on the seaward end was light throughout the area, with the heaviest rusting (20 percent) at 22 in. from the seaward end (Figure 11).

Figure 11. Heavy rusting on conduit of beam 19

92. The conduit of beam 19 was composed of three sections--the landward and seaward end sections and a midsection that was larger in diameter than either end section and fits over the ends of each section (Figure 12). The seaward end funnel housing was removed first to reveal

Figure 12. Profile of beam 19 showing the three sections of conduit

that the grout beneath was covered with a light coating of pinpoint rust specks. Also present were spots of rust that covered less than 30 percent of the surface (Photo 31). The conduit beneath this housing was moderately rusted, but compared to the conduit next to it that was not beneath the funnel housing, it was more heavily rusted. This indicates that the heavy rusting of the metal beneath the funnel was caused by some characteristic of the grout mixture that was not common to the concrete of the beam. This also appears to be true of the landward end of beam 9 (see paragraph 52).

93. The grout beneath the conduit at the seaward end was heavily rust-stained when the conduit was pried back (Photo 32). As the conduit was opened closer to the center of the beam, the residual stress in the steel caused the grout to crack. The grout cracked into small pieces approximately 1/2 in. long by 1/2-3/4 in. wide by 1/2 in. deep down to the level of the steel strands. As shown in Photo 32, the strands exposed at this time were moderately rusted. All along the inside face of the conduit where the grout was rust-stained, the conduit was heavily rusted. This section of the conduit was cut at the bottom; the top was only mildly rusted on the inside.

94. Next, the large central section of the conduit was cut on the topside of the beam. Immediately below the conduit for the full length of this section, the conduit was mildly rusted and the grout lightly rust-stained, particularly in the joints of the conduit. The grout in this section of the conduit cracked as it did in the other sections, but due to the larger diameter of the conduit in this area, the pieces were larger, averaging 1-1/2 in. long by 1-1/2 in. wide by 3/4 in. deep. The rust in this area was much milder than that at the seaward end, and it did not seem to have penetrated down to the steel. However, there were some small, light rust spots on the steel strands.

95. The pieces of grout from this section showed only a small bit of pitting-type rust between the steel and the grout. A few pieces of the grout at the grout-conduit interface indicated where air bubbles had been trapped beneath the conduit during the grout pumping operation (Photo 33).

96. At the landward end of this midsection where the two sections of conduit overlapped, there was a thin layer of grout between the two layers of metal conduit. This grout was very thin and broke into very small pieces. The grout, as well as the inside of the larger piece and the outside of the smaller piece of the conduit, was heavily corroded.

97. The steel strands in this central section were found to be closer to the top of the conduit than to the bottom; that is, the center line of the strand group was above the center line of the conduit, thereby effecting a closer proximity of the steel to the top of the conduit than to the bottom.

98. Observation of the grout in this area showed two different points of interest. First, where the air was trapped between the grout and the conduit, the grout was bubbly and weak, with voids between the grout and the conduit. Also, around these voids the grout appeared whitish. The second observation was related to the voids between the grout and the posttensioning steel. The grout at these spots also appeared white. The steel strands in beam 19 were arranged in concentric circles at the seaward end (eight strands circling four strands), but by the time this configuration reached the middle of the beam, the strands were bunched in no specific formation and touched each other, thus prohibiting the grout from getting between them. Also, as mentioned in paragraph 97, the strands were closer to the top than to the bottom of the conduit.

99. When the landward end of the conduit was opened, the steel was so close to the top of the conduit that at certain places there was barely 1/32 in. of grout cover. Some of the areas of the top strands were rusted because there was no cover at all. The grout broke into small pieces at the top of the conduit where the cover was extremely thin and larger pieces at the bottom where it was thick.

100. Photo 34 shows the rust stains on the grout inside the landward end funnel. These stains matched the rust on the inside of the housing (Photo 35). The grout was rust-stained over about 40 percent of the surface and had a good dense appearance. When the grout was chipped away, the steel strands below it were lightly to moderately rusted with light pitting and small spots of heavy rusting appearing on the strands near the landward end of the housing (Photo 36).

101. All the grout was then removed from the strands. The first general observations were that the strands were lightly to moderately rusted. The worst area of corrosion existed about 3 ft from the landward end on strands 1, 4, 6, and 7. These strands were at the top of the conduit and poorly protected by grout. The following subparagraphs describe the condition of each of the strands in beam 19.

<u>a</u>. <u>Strand 1.</u>

(1) Landward end: Continuous corrosion existed over

the entire end (0-10 in. = light rusting, moderate pitting and tarnishing; 10-24 in. = moderate rusting, light pitting, and moderate tarnishing; 24-32 in. = heavy rusting, moderate pitting and tarnishing).

(2) Seaward end: Continuous corrosion existed over the entire end (0-24 in. = light rusting, moderate pitting and tarnishing; 24-32 in. = light rusting, moderate pitting and tarnishing, with a thin line of rust at this end where two strands had rusted together).

(3) Midsection: Continuous corrosion existed over the entire section (32-64 in. from the landward end = light rusting, moderate pitting and tarnishing).

b. Strand 2.

(1) Landward end: Continuous corrosion existed over the entire end (0-10 in. = light rusting, moderate pitting, light tarnishing; 10-32 in. = moderate rusting and pitting, heavy tarnishing, with two strips of rust from 18 to 30 in. where adjacent strands had rusted together).

(2) Seaward end: Continuous corrosion existed over the entire end (0-32 in. = light rusting, moderate pitting and tarnishing).

(3) Midsection: Continuous corrosion existed over the entire section (32-64 in. from landward end = light rusting and pitting, moderate tarnishing).

c. Strand 3.

(1) Landward end: Continuous corrosion existed over the entire end (0-8 in. = light rusting, moderate pitting and tarnishing; 8-32 in. = moderate rusting, pitting, and tarnishing, with a line of rust from 11 to 25 in. where two strands had rusted together).

(2) Seaward end: Continuous corrosion existed over the entire end (0-32 in. = light rusting, moderate pitting and tarnishing, with a small line of rust at 22 in. where two strands had rusted together).

(3) Midsection: Continuous corrosion existed over the entire section (32-64 in. from the landward end = light rusting and pitting, moderate tarnishing).

d. Strand 4.

(1) Landward end: Continuous corrosion existed over the entire end (0-8 in. = light rusting and pitting, moderate tarnishing; 8-12 in. = moderate rusting,

pitting, and tarnishing; 12-32 in. = light rusting and pitting, moderate tarnishing).

(2) Seaward end: Continuous corrosion existed over the entire end (0-24 in. = light rusting and pitting, moderate tarnishing; 24-32 in. = light rusting and pitting, moderate tarnishing, with a heavy strip of rust where two strands had rusted together).

(3) Midsection: Continuous corrosion existed over the entire section (32-64 in. from the landward end = light rusting and pitting, moderate tarnishing, with a strip of rust over the entire section where two strands had come in contact and rusted).

e. Strand 5.

(1) Landward end: Continuous corrosion existed over entire end (0-32 in. = light rusting and pitting, moderate tarnishing). This end had heavier rust than did the midsection or seaward end.

(2) Seaward end: Continuous corrosion existed over the entire end (0-32 in. = light rusting and pitting, moderate tarnishing; 12-22 in. = a line of rust where two strands had rusted together).

(3) Midsection: Continuous corrosion existed over the entire section (32-64 in. from the landward end = light rusting and pitting, moderate tarnishing).

f. Strand 6.

(1) Landward end: Continuous corrosion existed over this end (0-24 in. = light rusting and pitting, moderate tarnishing; 24-32 in. = moderate rusting, light pitting, moderate tarnishing).

(2) Seaward end: Continuous corrosion existed over the entire end (0-8 in. = light rusting, moderate pitting and tarnishing with moderate amounts of calcium carbonate; 8-24 in. = light rusting and pitting, moderate tarnishing; 24-32 in. = moderate rusting, light pitting, moderate tarnishing, with a strip of rust from 30 to 32 in. due to contact between two strands).

(3) Midsection: Continuous corrosion existed over the entire section (32-64 in. from the landward end = moderate rusting, light pitting, moderate tarnishing). Over the entire section, most of the rusting was due to two strips of rust where adjacent strands had rusted to strand 6.

g. Strand 7.

(1) Landward end: Continuous corrosion existed over

the entire end (0-13 in. = light rusting, moderate pitting, light tarnishing; 13-32 in. = moderate rusting, light pitting and tarnishing). Rusting was heaviest where the strand was very close to the conduit.

(2) Seaward end: Continuous corrosion existed over the entire end (0-32 in. = light rusting, moderate pitting and tarnishing, with a strip of rust from 12 to 28 in. where two strands had rusted together).

(3) Midsection: Continuous corrosion existed over the entire section (32-64 in. from the landward end = moderate rusting, light pitting and tarnishing, with moderate amounts of grout stuck to the strand from 59 to 64 in.).

h. Strand 8.

(1) Landward end: Continuous corrosion existed over the entire end (0-32 in. = light rusting and pitting, moderate tarnishing, with two lines of rust from 13 to 16 and from 25 to 30 in. where the strand touched the conduit and another strand, respectively).

(2) Seaward end: Continuous corrosion existed over the entire end (0-32 in. = light rusting and pitting, moderate tarnishing, with two small, heavily rusted spots close to the end).

(3) Midsection: Continuous corrosion existed over the entire section (32-64 in. from the landward end = light rusting and pitting, moderate tarnishing).

i. Strand 9.

(1) Landward end: Continuous corrosion existed over the entire end (0-15 in. = light rusting, pitting and tarnishing, with heavy rust spots at 3 and 6 in.; 15-32 in. = light rusting, and moderate pitting and tarnishing, with a strip of rust due to two strands rusting together).

(2) Seaward end: Continuous corrosion existed over the entire end (0-8 in. = moderate rusting, light pitting, moderate tarnishing; 8-32 in. = light rusting and pitting, moderate tarnishing, with a line of rust from 18 to 22 in. due to contact between two strands).

(3) Midsection: Continuous corrosion existed over the entire section (32-64 in. from the landward end = light rusting and pitting, moderate tarnishing, with a line of rust from 54 to 61 in. where two strands had rusted together).

j. Strand 10.

(1) Landward end: Continuous corrosion existed over the entire end (0-8 in. = moderate rusting, light pitting, moderate tarnishing; 8-18 in. = light rusting and pitting, moderate tarnishing; 18-32 in. = moderate rusting, light pitting, moderate tarnishing). The rusting in this area was mainly due to the proximity of the strand to the conduit.

(2) Seaward end: Continuous corrosion existed over the entire end (0-24 in. = moderate rusting, light pitting, moderate tarnishing; 24-32 in. = light rusting and pitting, moderate tarnishing, with a strip of rust from 24 to 32 in. where two strands had rusted together).

(3) Midsection: Continuous corrosion existed over the entire midsection (32-64 in. from the landward end = moderate rusting, light pitting, moderate tarnishing, with the rusting between 32 and 60 in. mainly due to two strands rusting together).

k. Strand 11.

(1) Landward end: Continuous corrosion existed over the entire end (0-18 in. = light rusting and pitting, moderate tarnishing; 18-32 in. = light rusting, moderate pitting and tarnishing).

(2) Seaward end: Continuous corrosion existed over the entire end (0-18 in. = light rusting and pitting, moderate tarnishing; 18-32 in. = moderate rusting, light pitting, moderate tarnishing, with the rusting in the area between 18-32 in. due to two strands rusting together).

(3) Midsection: Continuous corrosion existed over the entire section (32-60 in. from the landward end = light rusting, pitting, and tarnishing; 60-64 in. from the landward end = heavy rusting, light pitting and tarnishing).

l. Strand 12.

(1) Landward end: Continuous corrosion existed over the entire end (0-32 in. = light rusting and pitting, moderate tarnishing).

(2) Seaward end: Continuous corrosion existed over the entire end (0-8 in. = moderate rusting, light pitting, moderate tarnishing; 8-32 in. = light rusting and pitting, moderate tarnishing, with rust from 19 to 32 in. due to two strands rusting together).

(3) Midsection: Continuous corrosion existed over the

entire section (32-64 in. from the landward end = light rusting and pitting, moderate tarnishing).

Condition of the
seaward end anchorage

102. The outside face of the seaward anchorage was very heavily rusted as was the landward end. Both of these faces had been directly subjected to seawater attack from the time their protective caps had come loose and detached. Similar to that on the landward end, the corrosion was deep on this face, nearly 1/8 in. deep in places. The stronger metal below the corroded flakes was also heavily rusted. This end did not contain a tightening collar as the landward end did, but the strand ends were just as heavily rusted (Photo 37).

103. The edges of the plate were moderately rusted on three edges, and the fourth edge was heavily rusted. There was corrosion on the full depth of the heavily rusted edge, but the other edges were heavily rusted only on the outer halves. The inside halves were just heavily tarnished.

104. The inside face of the plate was not rusted at all. The metal surface was heavily tarnished, as were the edges, with some moderate pitting of the metal but no rust (Photo 38).

PART III: OBSERVATIONS AND TEST RESULTS IN THE SECOND LABORATORY INVESTIGATION

105. The beams in this investigation (1, 6, and 11) were wrapped in a waterproof, bituminous membrane at Treat Island prior to shipment to the WES. This was done to determine whether drying during transportation and laboratory storage had affected the results of corrosion found in the first laboratory investigation.

106. When the membrane covering the beams was opened subsequent to return, it was observed that the surface of the concrete was still moist with seawater. The entire beam surface was damp, and in pockets where moisture could form were small pools of seawater. The pools of water around the conventional reinforcement were full of rust particles and had turned the rusty brown color of the metal (Photos 39 and 40).

Beam 1

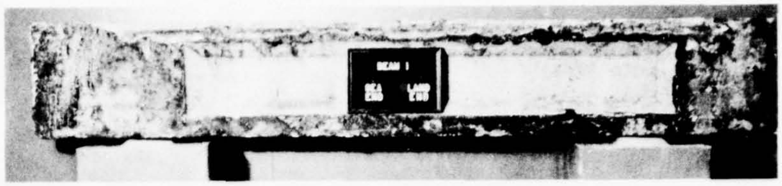
107. The as-received condition of beam 1 after the bituminous membrane had been removed is shown in Figure 13. Some of the concrete had spalled from the top edges of the beam exposing the conventional reinforcement at the seaward end on one side (Figure 13b) and along most of the top edge on the other (Figure 13a). Both end protective caps were still intact and did not show excessive wear.

108. The landward end of this beam was protected by an air-entrained concrete cap bonded to a cold joint with no surface treatment. This end had a flush-type anchorage. The seaward end had an external-type anchorage protected by an air-entrained cap bonded to the beam by using a retarding agent.

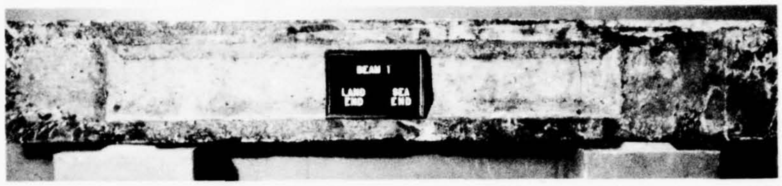
109. The strands of the tendon in this beam were arranged in a circular fashion. For purposes of identification, the strands were numbered as shown in Figure 14 (looking from the landward end).

Condition of the landward end anchorage

110. The 1-1/4-in. length of each strand that protruded from the

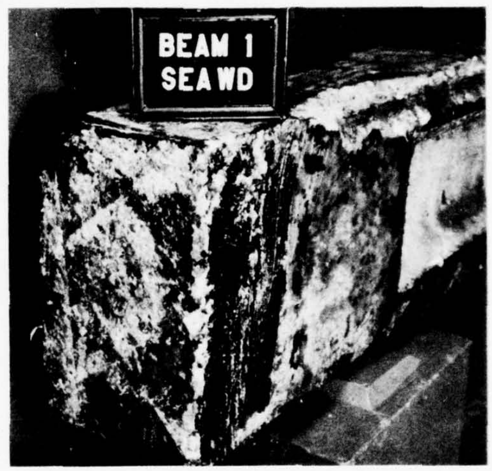


a. Side view



b. Side view

c. Landward end view



d. Seaward end view

Figure 13. As-received condition of beam 1

end of the anchorage was either heavily rusted or tarnished. The mortar within the steel coil of this end anchorage was an epoxy mortar. The two other beams that had this type posttensioning and were evaluated under this program (beams 3 and 6) did not have this epoxy in the mortar of the end anchor. One of the observations made when this end was opened was that the strands were either partially or entirely coated with epoxy. It appeared that after the epoxy mortar had been placed around the end anchorage, some of the epoxy bled out of the mortar and

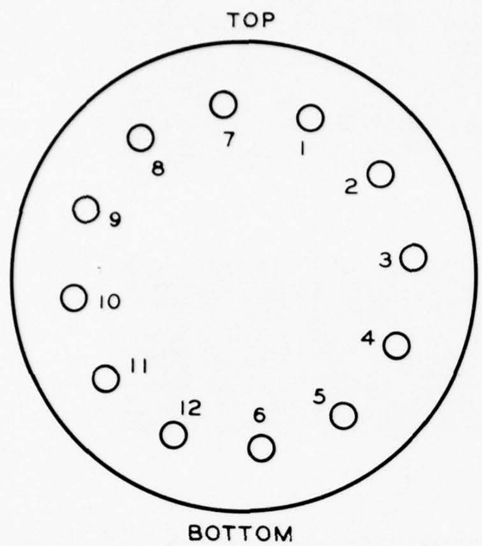


Figure 14. Landward end anchorage, beam 1

coated the strands. All the strands were heavily corroded, and using the nomemclature in Figure 14, the steel strands were corroded as follows:

Strand	Condition
1	Heavily rusted
2	Heavily rusted
3	Heavily rusted
4	Covered with epoxy
5	Partially covered with epoxy and heavily tarnished
6	Partially covered with epoxy and heavily tarnished
7	Covered with epoxy except at base where it was heavily rusted
8	Partially covered with epoxy and lightly rusted
9	Partially covered with epoxy and lightly rusted
10	Covered with epoxy
11	Covered with epoxy
12	Partially covered with epoxy and lightly rusted

111. After the conditions described in paragraph 110 were recorded, the epoxy was broken from the strands exposing heavily rusted strands. Thus, the epoxy that had coated the strands did not retard the corrosion process.

112. The coil of wire around the end anchor was relatively free of rust, with less than 1 percent of the surface area rusted. The

corrosion that did exist was mostly light rusting on the first and second turns of wire. The rest of the turns were covered with tarnish. Below the coils of wire the strands of posttensioning steel were all moderately to heavily rusted, especially where there was strand contact with the coils of wire used as part of the anchorage.

Condition of the conduit

113. In the first 17 in. from the landward end of the beam, the conduit was free of rust. The only exception occurred just inside the landward end anchorage where the conduit met the end anchorage. This condition was similar to that in beam 6 shown in Photo 41. Where the two dissimilar metals came in contact, the rust was from light to moderate and covered about 1 in. around the joint. From 17 to 23 in., the bottom half of the conduit was covered with heavy amounts of rust, with the top half moderately rusted from 18 to 19 and from 20 to 22 in. The midsection of the conduit was not rusted, but the luster of the metal had been dulled appreciably. From the seaward end, the conduit was also heavily dulled out to 18 in. but not rusted. From 18 to 42 in. from the seaward end, there were moderate amounts of rust on the conduit.

114. As found previously (see paragraph 40), in the areas where the conduit was dulled there was a covering of hardened paste from the concrete, and the conduit was not rusted. Where the conduit was still lustrous, there was no covering of hardened paste and the lustrous areas contained rust, generally light to moderate in severity. It appears that where the conduit was dulled, a bond existed between the paste and the conduit. Since the bond was good here, either less rust developed or the layer of paste covered the rust. Where the conduit was lustrous, there appeared to be no bond between the paste and conduit. This lack of bond allowed the conduit to be rusted.

115. Along the entire length of the conduit on the inside, the top half was free of rust; however, this top half was tarnished heavily. The bottom half of the inside was rusted to a moderate degree. This rusted area was defined by a change in color of the tarnished portion of the conduit. On the bottom half the tarnishing was a lighter color than that on the top half, and the demarcation line between areas was

sharp and definite. The rusting on the bottom half was light to moderate over the entire length of the conduit, being heavier in the middle than at the ends and also heavier in the joints between segments of the conduit than on the ridges of the conduit. Between 15 and 23 in. from the landward end, there was a strip of heavy rusting where a steel strand had come in contact with the inside of the conduit and rusted. This condition existed again from 35 to 41 in. from the landward end.

116. The following subparagraphs describe the condition of the strands of beam 1.

a. Strand 1.

(1) Landward end: Continuous corrosion existed over the entire end (0-32 in. = moderate rusting, heavy pitting and tarnishing, with a strip of heavy rust from 14 to 19 in. due to contact rusting between bars).

(2) Seaward end: Continuous corrosion existed over the entire end (0-12 in. = light rusting, moderate pitting and tarnishing; 12-32 in. = moderate rusting, pitting, and tarnishing, with two strips of heavy rusting due to strand contact, one from 28 to 32 in. from the landward end and the other the entire length of the end).

(3) Midsection: Continuous corrosion existed over the entire section (32-48 in. from the landward end = light rusting, heavy pitting and tarnishing; 32-48 in. from the seaward end = moderate rusting, heavy pitting and tarnishing, with one strip of contact rusting from 38 to 48 in. from the landward end; and over the entire section the amount of grout that stuck to the strand was heavy).

b. Strand 2.

(1) Landward end: Continuous corrosion existed over entire end (0-32 in. = moderate rusting, heavy pitting and tarnishing, with two strips of heavy contact rusting, one from 12 to 18 and the other from 10 to 19 in.).

(2) Seaward end: Continuous corrosion existed over the entire end (0-32 in. = light rusting, moderate pitting, and heavy tarnishing, with a strip of contact rusting running the entire length of this section, heaviest from 28 to 32 in. from the end).

(3) Midsection: Continuous corrosion existed over the entire section (32-40 in. from the landward end =

moderate rusting, heavy pitting and tarnishing; 40-49 in. from the landward end = heavy rusting, pitting, and tarnishing; 32-47 in. from the seaward end = moderate rusting, heavy pitting and tarnishing, with two heavy strips of contact rusting, one from 32 to 48 in. from the seaward end and the other from 32 to 59 in. from the seaward end).

c. Strand 3.

(1) Landward end: Continuous corrosion existed over the entire end (0-9 in. = moderate rusting, heavy pitting and tarnishing; 9-25 in. = heavy rusting, pitting, and tarnishing; 25-32 in. = moderate rusting, heavy pitting and tarnishing, with a strip of heavy rusting due to bar-to-bar contact from 15 to 32 in.).

(2) Seaward end: Continuous corrosion existed over the entire end (0-12 in. = light rusting, heavy pitting and tarnishing; 12-32 in. = moderate rusting, heavy pitting and tarnishing).

(3) *Midsection:* Continuous corrosion existed over the entire section (moderate rusting, heavy pitting and tarnishing over the entire section, with a strip of heavy rust from 32 to 60 in. from the seaward end).

d. Strand 4.

(1) Landward end: Continuous corrosion existed over the entire end (0-32 in. = moderate rusting, heavy pitting and tarnishing, with two strips of contact rust, one from 9 to 32 and the other from 17 to 32 in.).

(2) Seaward end: Continuous corrosion existed over the entire end (0-9 in. = light rusting, heavy pitting and tarnishing; 9-32 in. = moderate rusting, heavy pitting and tarnishing, with two strips of heavy rust, one from 11 to 32 and the other from 28 to 32 in. from the end).

(3) Midsection: Continuous corrosion existed over the entire section (32-64 in. from the landward end = moderate rusting and pitting, heavy tarnishing, with two strips of heavy contact rusting, one extending over the full section and the other from 32 to 60 in. from the seaward end).

e. Strand 5.

(1) Landward end: Continuous corrosion existed over the entire end (0-32 in. = moderate rusting, heavy pitting and tarnishing, with one strip of heavy rust due to contact between bars extending the full length of this end).

(2) Seaward end: Continuous corrosion existed over the entire end (0-32 in. = moderate rusting, heavy pitting and tarnishing, with a strip of heavy rust due to contact between bars extending the full length of this end).

(3) Midsection: Continuous corrosion existed over the entire section (32-64 in. from the landward end = moderate rusting, heavy pitting, moderate tarnishing, with one strip of heavy rust extending the full length of the section and another from 37 to 42 in. from the landward end).

f. Strand 6.

(1) Landward end: Continuous corrosion existed over the entire end (0-32 in. = moderate rusting, heavy pitting and tarnishing).

(2) Seaward end: Continuous corrosion existed over the entire end (0-12 in. = moderate rusting and pitting, heavy tarnishing; 12-20 in. = moderate rusting, light pitting, moderate tarnishing; 20-32 in. = moderate rusting, heavy pitting and tarnishing).

(3) Midsection: Continuous corrosion existed over the entire section (32-40 in. from the landward end = moderate rusting, heavy pitting and tarnishing; 40-53 in. from the landward end = moderate rusting, pitting, and tarnishing; 32-43 in. from the seaward end = moderate rusting and pitting, heavy tarnishing; and over the entire midsection, various small strips of heavy rust due to bar-to-bar contact).

g. Strand 7.

(1) Landward end: Continuous corrosion existed over the entire end (0-14 in. = light rusting, heavy pitting and tarnishing; 14-32 in. = moderate rusting, heavy pitting and tarnishing, with a strip of heavy rust from 15 to 19 in. due to contact rusting of two bars).

(2) Seaward end: Continuous corrosion existed over the entire end (0-32 in. = light rusting, moderate pitting and tarnishing, with a moderate strip of contact rust from 6 to 10 in.).

(3) Midsection: Continuous corrosion existed over the entire section (32-45 in. from the landward end = moderate rusting and pitting, heavy tarnishing; 32-51 in. from the seaward end = moderate rusting, pitting, and tarnishing; and a strip of bar-to-bar contact rust extending over the entire section).

h. Strand 8.

(1) Landward end: Continuous corrosion existed over the entire end (0-32 in. = moderate rusting and pitting, heavy tarnishing, with a strip of contact rust from 26 to 32 in. from the end).

(2) Seaward end: Continuous corrosion existed over the entire end (0-14 in. = light rusting, moderate pitting and tarnishing; 14-32 in. = moderate rusting, pitting, and tarnishing).

(3) Midsection: Continuous corrosion existed over the entire section (moderate rusting and pitting, and heavy tarnishing over the entire section, with a strip of heavy contact rusting over the whole length of this section).

i. Strand 9.

(1) Landward end: Continuous corrosion existed over the entire end (0-32 in. = moderate rusting and pitting and heavy tarnishing, with a strip of contact rusting extending from 10 to 32 in.).

(2) Seaward end: Continuous corrosion existed over the entire end (0-32 in. = light rusting, heavy pitting and tarnishing).

(3) Midsection: Continuous corrosion existed over the entire section (32-42 in. from the landward end = moderate rusting, heavy pitting, moderate tarnishing; 32-54 in. from the seaward end = moderate rusting, pitting, and tarnishing; and a strip of heavy rusting over the entire section from contact rusting).

j. Strand 10.

(1) Landward end: Continuous corrosion existed over the entire end (0-32 in. = moderate rusting, pitting, and tarnishing, with a strip of heavy rust appearing from 10 to 21 in. and again from 27 to 32 in. due to bar-to-bar contact).

(2) Seaward end: Continuous corrosion existed over the entire end (0-32 in. = moderate rusting, heavy pitting and tarnishing, with heavy rust marks on the strand from 6 to 10 in. from the end, indicating the presence of strand-to-conduit contact rusting; and a strip of moderate bar-to-bar contact rusting over the entire end).

(3) Midsection: Continuous corrosion existed over the entire section (32-40 in. from the landward end = moderate rusting and pitting, heavy tarnishing;

and two strips of heavy contact rust, one from 32 to 52 in. from the seaward end and the other over the entire length of the section).

k. Strand 11.

(1) Landward end: Continuous corrosion existed over the entire end (0-14 in. = heavy rusting, pitting, and tarnishing, with a strip of heavy contact rusting from 6 to 7 in.; 14-22 in. = moderate rusting and pitting and heavy tarnishing; 22-32 in. = moderate rusting, light pitting, and moderate tarnishing).

(2) Seaward end: Continuous corrosion existed over the entire end (0 to 32 in. = moderate rusting, pitting, and tarnishing, with rust from 6 to 10 in., indicating contact between the bar and the conduit (similar to that on the midsection discussed in paragraph 126g), and with a continuous strip of heavy contact rust over the whole end due to bar contact).

(3) Midsection: Continuous corrosion existed over the entire section (32-40 in. from the landward end = moderate rusting, light pitting, moderate tarnishing; 32-56 in. from the seaward end = moderate rusting, pitting, and tarnishing; and a strip of heavy rust due to bar-to-bar contact over the entire section).

l. Strand 12.

(1) Landward end: Continuous corrosion existed over the entire end (0-14 in. = moderate rusting and pitting, heavy tarnishing; 14-32 in. = heavy rusting, moderate pitting, heavy tarnishing, with a strip of heavy contact rust from 18 to 22 in.).

(2) Seaward end: Continuous corrosion existed over the entire end (0-11 in. = moderate rusting, pitting, and tarnishing; 11-32 in. = moderate rusting, heavy pitting and tarnishing, with a strip of heavy contact rust from 12 to 32 in. from the end).

(3) Midsection: Continuous corrosion existed over the entire section (32-48 in. from the landward end = moderate rusting and pitting, heavy tarnishing; 32-48 in. from the seaward end = moderate rusting, pitting, and tarnishing; and two spots of heavy bar-to-bar contact rust in this section, one from 40 to 41 and the other from 50 to 51 in. from the landward end).

Condition of the
seaward end anchorage

117. This end anchorage also had epoxy that bled from the epoxy mortar pumped between the coils of the anchorage, and as at the landward end, the 1-1/4 in. of strand on the outside of the anchorage was heavily rusted, even beneath the epoxy (Photos 42 and 43). The coils of wire that surrounded the posttensioning strands were free of rust with the exception of one tiny spot on the first coil that was lightly rusted. The rest of the coils were only tarnished.

Beam 6

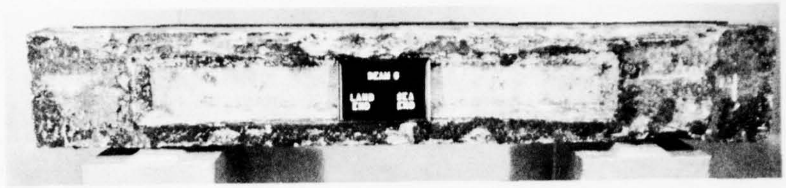
118. The as-received condition of beam 6 after the removal of the protective bituminous membrane is shown in Figure 15. Comparison of the two sides shows that spalling occurred only on one side at the top edge of the beam. Figures 15c and 15d show the conditions of the landward and seaward end protective caps.

119. The landward end of this beam was protected by a plug of sand-cement mortar over the end of the anchorage of the beam. This end was in good shape with the exception of one small spalled area at the top corner. The sand-cement mortar plug covered a flush-type posttensioning anchorage and was found to be in good shape.

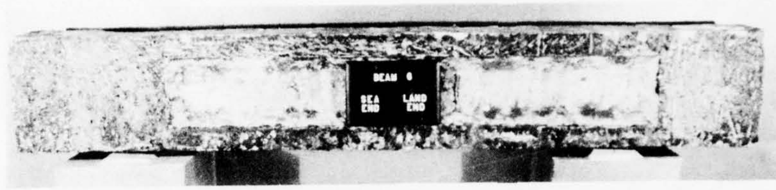
120. The seaward end of this beam was protected by an epoxy concrete end cap with reinforcement (Figure 15d). As shown in this figure, the end cap was unaffected by exposure to the marine environment. There were no spalled areas, and the edges were sharp and unbroken. One corner showed slight crushing caused by moving the beam.

Condition of the
landward end anchorage

121. The 1-1/4-in. lengths of strand that extended from the end of the anchorage were completely free of rust. The strands were free of mortar and heavily tarnished from age but did not show any rusting or pitting. Likewise the coils of steel around the strands were unrusted. There was cement bonded to the steel and the coils were tarnished, but



a. Side view



b. Side view

c. Landward end view

d. Seaward end view

Figure 15. As-received condition of beam 6

no rust was seen at this end (Photos 44 and 45).

<u>Condition of the conduit</u>

122. The outside of the conduit at the landward end of this beam was slightly rusted. The rust was spread over the end but was concentrated and heavy in a few small spots. Where no rust appeared, the conduit was dulled by bonded cement from the concrete. The midsection of this conduit was more rusted than were the landward or seaward ends,

but still it was only lightly rusted. In this section, there were two heavily corroded areas (Photos 46 and 47), each about 2 sq in., as well as numerous small holes in the conduit caused by heavy rusting. These small holes were basically between the two larger, heavily rusted spots previously described in this paragraph (between 41 and 49 in. from the seaward end). In this area, the conduit was moderately covered with rust. The seaward end was lightly rusted, similar to the landward end. The bond between the metal and the cement was good since the conduit was heavily dulled and coated with a cement film. Very little pitting and only minute spots of heavy rusting were observed.

123. The inside of this conduit, both at the landward and seaward ends, was lightly rusted; rust appeared mainly on the joints between the segments of the conduit. The part of the conduit that was not rusted was lightly to moderately tarnished. Some of the metallic luster that was on the surface when the conduit was new was still present (Photo 48). The midsection of the conduit was moderately rusted, corresponding to the more heavily rusted midsection of the outside of the conduit. The rust was heavier in the joints and on the surface, and the unrusted surfaces were less lustrous (Photo 49).

124. Before opening the conduit to inspect the strands of post-tensioning steel, the landward and seaward ends of the tendons were cut from the conduit to expose the steel and grout pattern and to see if this would relieve any residual stress in the steel. Photo 50 shows the landward end immediately after it had been cut. From this photograph, it can be seen that the individual strands were very close to the outside of the conduit and that some of the strands came in contact with the inside of the conduit and with other strands in the conduit. The grout was dense and free from air voids in this cross section. The seaward end cut was similar to the landward end cut except that the strands were bunched toward the top of the conduit. While the conduit was not cut lengthwise, the cross section remained as shown in Photo 50, and the steel did not return to its untensioned length. However, when the conduit was finally cut and the grout cracked due to the release of radial constraint, the strands shortened about 5/32 in., as shown in

Photo 51 of the seaward end cut. This indicated that the bond between the steel and the grout was good enough to hold the residual posttensioning force even when the anchorages had been cut. Only when the conduit was opened did the bond between steel and grout break.

125. An interesting observation can be made from Photo 51 regarding the effectiveness of the posttensioning operation of this beam. When the conduit was cut open, 9 of the 12 posttensioning strands returned to their untensioned lengths. Three of the strands did not. Since the radial constraint of the conduit had been released when it was cut and the bond between the strands broken, these three strands did not shorten because they were already in their untensioned state. It appears that when the beams were posttensioned at the outset of this project, either these three strands were never posttensioned, or they lost their posttensioning force either immediately or during the 13 years between the start of the project and the time when they were cut. This also indicates that the loading beam 6 underwent during structural testing was supported by only 9 posttensioned strands, instead of the expected 12.

126. Once the grout had been removed from the steel strands, the strands were cataloged for their rust. The following subparagraphs describe the condition of each strand in beam 6.

a. Strand 1.

(1) Landward end: Continuous corrosion existed over the entire end (0-10 in. = moderate rusting, pitting, and tarnishing; 10-32 in. = moderate rusting, heavy pitting and tarnishing; and over the entire length of this end, two strips of heavy rust due to bar-to-bar contact).

(2) Seaward end: Continuous corrosion existed over the entire end (0-32 in. = moderate rusting, heavy pitting and tarnishing, with two strips of rust due to bar-to-bar contact from 23 to 32 in.).

(3) Midsection: Continuous corrosion existed over the entire section (32-64 in. from the landward end = moderate rusting, heavy pitting and tarnishing, with two strips of heavy rust from bar-to-bar contact, one from 32 to 64 and the other from 32 to 61 in. from the landward end).

b. Strand 2.

(1) Landward end: Continuous corrosion existed over the entire end (0-32 in. = moderate rusting and pitting, heavy tarnishing, with two strips of heavy rust over the entire end from bar-to-bar contact rusting).

(2) Seaward end: Continuous corrosion existed over the entire end (0-13 in. = light rusting, moderate pitting and tarnishing; 13-32 in. = moderate rusting, heavy pitting and tarnishing, with a heavy strip of rust from 29 to 31 in., and a moderate strip of rust due to bar contact throughout the end).

(3) Midsection: Continuous corrosion existed over the entire section (moderate rusting and pitting and heavy tarnishing over the entire midsection, with two strips of contact rust from 32 to 61 in. from the landward end).

c. Strand 3.

(1) Landward end: Continuous corrosion existed over the entire end (0-10 in. = heavy rusting and pitting, moderate tarnishing; 10-32 in. = moderate rusting and pitting, heavy tarnishing, with two strips of heavy rust from 10 to 32 in. due to contact rusting).

(2) Seaward end: Continuous corrosion existed over the entire end (0-13 in. = light rusting, moderate pitting, heavy tarnishing; 13-32 in. = moderate rusting, heavy pitting and tarnishing. The rust on this strand was heavier on the side of the strand facing into the center of the conduit).

(3) Midsection: Continuous corrosion existed over the entire section (32-58 in. from the landward end = moderate rusting, heavy pitting and tarnishing; 58-64 in. from the landward end = heavy rusting, pitting, and tarnishing, with two strips of heavy rust due to bar-to-bar contact from 32 to 61 in. from the landward end).

d. Strand 4.

(1) Landward end: Continuous corrosion existed over the entire end (0-32 in. = moderate rusting and pitting, heavy tarnishing, with two strips of heavy rust over the entire end due to bar-to-bar contact).

(2) Seaward end: Continuous corrosion existed over the entire end (0-13 in. = light rusting, moderate pitting, heavy tarnishing; 13-25 in. = moderate

rusting and pitting, heavy tarnishing; 25-32 in. = heavy rusting, moderate pitting and tarnishing; and over the entire end, two strips of heavy rust due to bar-to-bar contact).

(3) Midsection: Continuous corrosion existed over the entire section (over the entire midsection moderate rusting and pitting and heavy tarnishing, with two strips of rusting due to bar contact, one from 32 to 58 and the other from 32 to 56 in. from the landward end).

e. Strand 5.

(1) Landward end: Continuous corrosion existed over the entire end (0-32 in. = moderate rusting and pitting and heavy tarnishing, with two strips of heavy rust over the entire length of this end due to bar contact).

(2) Seaward end: Continuous corrosion existed over the entire end (0-10 in. = light rusting and pitting, heavy tarnishing; 10-26 in. = moderate rusting, pitting, and tarnishing; 26-32 in. = heavy rusting, moderate pitting and tarnishing).

(3) Midsection: Continuous corrosion existed over the entire section (moderate rusting, pitting, and tarnishing over the entire section, with two heavy strips of rust due to bar contact, one from 32 to 59 and the other from 32 to 64 in. from the landward end).

f. Strand 6.

(1) Landward end: Continuous corrosion existed over the entire end (0-32 in. = moderate rusting, light pitting, moderate tarnishing, with two strips of heavy rust over the entire end due to bar-to-bar contact).

(2) Seaward end: Continuous corrosion existed over the entire end (0-13 in. = light rusting and pitting, heavy tarnishing; 13-32 in. = moderate rusting, pitting, and tarnishing, with one heavy strip of rust from 28 to 32 in. due to bar-to-bar contact).

(3) Midsection: Continuous corrosion existed over the entire section (32-64 in. from the landward end = moderate rusting, pitting, and tarnishing; and two heavily rusted strips, one from 32 to 51 in. from the landward end and the other the entire length of the midsection, due to contact rusting).

g. Strand 7.

(1) Landward end: Continuous corrosion existed over the entire end (0-10 in. = moderate rusting, heavy pitting and tarnishing; 10-32 in. = moderate rusting, light pitting, moderate tarnishing; and two strips of heavy rust due to bar contact, one over the entire length of this end and the other from 18 to 32 in.).

(2) Seaward end: Continuous corrosion existed over the entire end (0-32 in. = moderate rusting and pitting, heavy tarnishing).

(3) Midsection: Continuous corrosion existed over the entire section (over the entire midsection moderate rusting, light pitting, moderate tarnishing, with one strip of heavy rust due to bar contact the full length of the section and two smaller strips, one from 33 to 38 and the other from 51 to 57 in. from the landward end; and from 48 to 51 and from 54 to 56 in. from the landward end, spots of heavy rust on the strand (Photo 52) where it came in contact with the inside of the conduit).

h. Strand 8.

(1) Landward end: Continuous corrosion existed over the entire end (0-32 in. = moderate rusting, pitting, and tarnishing, with four small strips of heavy rust due to bar contact at various spots over this end).

(2) Seaward end: Continuous corrosion existed over the entire end (0-13 in. = light rusting and pitting, heavy tarnishing; 13-32 in. = moderate rusting, light pitting, moderate tarnishing).

(3) Midsection: Continuous corrosion existed over the entire section (moderate rusting, pitting, and tarnishing over the entire section, with two strips of heavy rust due to bar contact, one from 39 to 64 and the other from 56 to 64 in. from the landward end).

i. Strand 9.

(1) Landward end: Continuous corrosion existed over the entire end (0-10 in. = moderate rusting and pitting, heavy tarnishing; 10-32 in. = moderate rusting, pitting, and tarnishing, with two strips of heavy bar-to-bar contact rusting, one from 19 to 32 and the other from 23 to 26 in.).

(2) Seaward end: Continuous corrosion existed over the entire end (0-10 in. = light rusting and pitting, moderate tarnishing; 10-32 in. = moderate rusting, light pitting, moderate tarnishing, with two strips of heavy rust from 28 to 32 in.).

(3) Midsection: Continuous corrosion existed over the entire section (moderate rusting, light pitting, and moderate tarnishing over the entire midsection, with two strips of heavy rust along the entire length of the section due to bar-to-bar contact).

j. Strand 10.

(1) Landward end: Continuous corrosion existed over the entire end (0-32 in. = moderate rusting, pitting, and tarnishing, with one strip of heavy rusting from bar contact over the entire end).

(2) Seaward end: Continuous corrosion existed over the entire end (0-13 in. = light rusting and pitting, heavy tarnishing; 13-24 in. = moderate rusting and pitting, heavy tarnishing; 24-32 in. = heavy rusting, moderate pitting, heavy tarnishing; and strips of heavy contact rusting from 0 to 10 and from 29 to 32 in.).

(3) Midsection: Continuous corrosion existed over the entire section (32-45 in. from the landward end = moderate rusting, pitting, and tarnishing; 45-64 in. from the landward end = moderate rusting, light pitting, moderate tarnishing, with two sections, one from 49 to 51 and the other from 53 to 55 in. from the landward end, with rust due to contact between the strand and the conduit (Photo 52); and one strip of rust due to bar contact extending the entire length of the section).

k. Strand 11.

(1) Landward end: Continuous corrosion existed over the entire end (0-32 in. = moderate rusting, light pitting, moderate tarnishing, with two strips of heavy rust due to bar-to-bar contact extending over the entire length of this end).

(2) Seaward end: Continuous corrosion existed over the entire end (0-13 in. = light rusting, moderate pitting, heavy tarnishing; 13-32 in. = moderate rusting and pitting, heavy tarnishing, with a strip of heavy contact rust from 29 to 32 in.).

(3) Midsection: Continuous corrosion existed over the entire section (moderate rusting, light pitting, and heavy tarnishing over the entire midsection, with one strip of heavy rust extending the entire length of this section).

l. Strand 12.

(1) Landward end: Continuous corrosion existed over

the entire end (0-20 in. = moderate rusting, pitting, and tarnishing; 20-32 in. = moderate rusting, light pitting, moderate tarnishing; and two strips of heavy rust due to contact between bars, one extending from 0 to 10 in. and the other the entire length of this end).

(2) Seaward end: Continuous corrosion existed over the entire end (0-15 in. = light rusting and pitting, heavy tarnishing; 15-32 in. = moderate rusting and pitting, heavy tarnishing).

(3) Midsection: Continuous corrosion existed over the entire section (moderate rusting, light pitting, and moderate tarnishing over the entire section, with intermittent spots of heavy rusting due to strand-to-strand contact over the whole section).

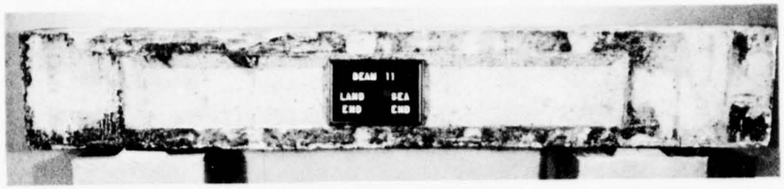
Condition of the
seaward end anchorage

127. The ends of the strands extending from the seaward end anchorage were all heavily tarnished but not rusted. The only rust present on these strands was directly on the tips of the steel. Some pitting on the strands and a small amount of epoxy from the epoxy concrete cap used to protect the anchorage were present. The steel coils of the anchorage were lightly rusted at various spots, and those areas of coils not rusted were still lustrous and unpitted (Photo 53).

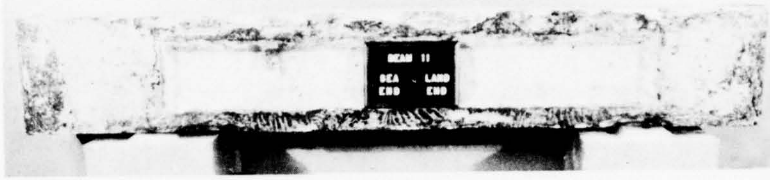
128. For all 12 strands, the length of the strand beneath the end anchorage coil was moderately rusted and pitted and heavily tarnished. There was a distinct line of difference between the steel encased by the sand-cement mortar and that exposed to the epoxy end cap.

Beam 11

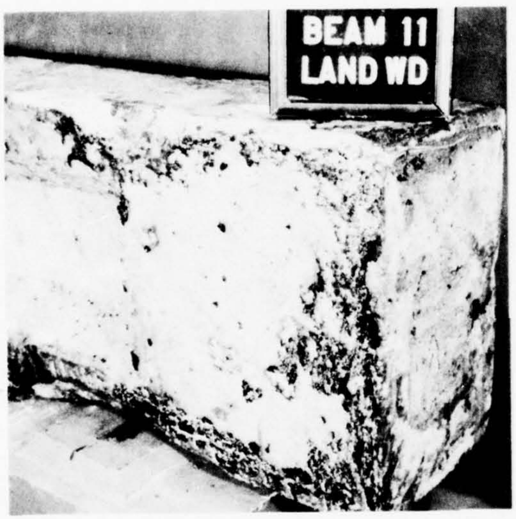
129. The as-received condition of beam 11 is shown in Figure 16. The concrete had spalled from the top edges on both sides of the beam and from one side at the bottom, exposing the conventional reinforcement to saltwater attack. The beam had a protective end cap at the seaward end and a plug over a flush end anchorage at the landward end. Both types of end protection were in excellent shape at the time of inspection.



a. Side view



b. Side view



c. Landward end view

d. Seaward end view

Figure 16. As-received condition of beam 11

130. The landward end of beam 11 was protected by an epoxy end plug inside the conventional concrete beam. The seaward end was protected by a full epoxy concrete cap over both the anchorage and the end faces of the beam.

Condition of the landward end anchorage

131. The epoxy end anchorage plug that protected this end

anchorage did not compact as well as it could have (Photos 54 and 55). The edges of the end anchorage plate were rusted along the outside of the edge where it came in contact with the epoxy plug. This end anchorage, when compared with that of the seaward end, was much more corroded. The anchorage consisted of a 3/4-in.-thick rectangular end plate, nine washers, and a bolt used to posttension the steel rod. Photo 56 shows the rust to the outside of this plate. The bolt was 100 percent covered with rust and pitting, but the end of the rod that it was threaded onto had very little rust on it. Although the bolt was covered with rust, the coating was only a thin layer and no deep damage had been done to the bolt or posttensioning rod. The outermost washer was heavily covered with rust as were the exposed edges of all the other washers. The face of the rectangular plate was moderately rusted, mostly on the outside of the plate face. The rusting gave way to tarnishing toward the center. The inside face of the landward end anchorage was not at all rusted, but the metal was heavily tarnished as shown in Photo 57.

Condition of the conduit

132. The outside of this conduit was the least corroded of all the conduits encountered in this study. With the exception of a lightly rusted section about 36 in. from the seaward end, the conduit was free from rust and highly lustrous. Contrary to the behavior of the conduits previously discussed, in which the shiny portions were rusted, this conduit did not behave in this way. There appears to have been no bond between the cement paste and the conduit because pieces of concrete removed from around the conduit had the imprint of the outside of the conduit in them; the surface of this imprint had no rust stains and appeared almost highly polished, indicating no bond (Photo 58). The area that was lightly rusted (about 16 in. long) constituted less than one percent of the surface area. In this area, the luster of the metal conduit was somewhat reduced. The amount of concrete paste stuck to the conduit was light in this area, but it was greater than that in any other area on the conduit.

133. The seaward end funnel housing was opened first. It was

discovered that the grout that had been pumped inside this housing did not reach all the areas it had been intended to reach. The small end of the cone was not filled, thereby indicating that the amount of pressure used to pump the grout had not been high enough to fill the conduit or the grout began to set before it reached the end of the housing. As the housing was opened further, it was observed that the grout mix had been pumped farther into the funnel housing at the bottom of the conduit than at the top. Also, when the grout was removed, the bottom half of the housing was rusted where it was covered by grout and not rusted (but heavily tarnished) where the grout did not penetrate. Photo 59 shows the rust on the bottoms of the funnel housing and the conduit and also pieces of grout that did penetrate into the funnel housing. The top half of the housing was lightly rusted and pitted, but the rust was very light in comparison with that shown in the photograph. Some light, chalky grout was found in the housing. It was filled with tiny air bubbles and broke very easily.

134. The conditions at the seaward end funnel housing were matched by those at the landward end. The grout did not penetrate to the full extent of the housing. Where there was no grout cover under the top half, there was only very light rusting on the conduit. At the bottom of the housing, the grout was rust-stained and had penetrated farther into the funnel than it did at the top. Below the grout the conduit was rusted, and some of the grout appeared white, chalky, and soft.

135. The beam's conduit was cut to examine the inside, and after the grout had been removed, the conduit was found to be heavily rusted on the bottom half. Starting from the landward end, the bottom half was heavily rusted both on the ridges and in the joints of the conduit to the midportion of the beam. The rust was continuous and about 1 in. wide over the whole length. On both sides of the rusted area were border areas covered with a film that, although not rust, had caused a dulling of the conduit on either side of the rust (Photo 60). On the upper half of the conduit, the metal was not rusted and appeared lustrous. Some light rust was noted in the joints between segments. Toward the seaward end of the beam, the rust on the bottom half of the conduit

remained just as heavy as that at the landward end but was not continuous over the whole length. There were lengths of this end that were not rusted heavily at all. The top of the conduit at this end was also lightly rusted.

136. The bolt at the seaward end anchorage that was used to post-tension the rod was removed to determine how far the corrosion had reached. The threads of the rod did not have any rust where they were covered by the bolt, and the faces of the washers were likewise unrusted. However, where the grout from inside the conduit came through the holes in the plate and washers, there was rust on the threads (Photo 61). Also, the plate itself was not very rusted except right at the hole where water and air from the grout mixture provided two of the necessary elements of corrosion (Photo 62).

137. The following subparagraphs describe the condition of the bar in beam 11.

a. Landward end: Continuous corrosion existed over the entire end (0-22 in. = moderate rusting, heavy pitting and tarnishing; 22-32 in. = moderate rusting, pitting, and tarnishing).

b. Seaward end: Continuous corrosion existed over the entire end (0-18 in. = moderate rusting and pitting, heavy tarnishing; 18-32 in. = moderate rusting, pitting, and tarnishing).

c. Midsection: Continuous corrosion existed over the entire section (32-64 in. from the landward end = moderate rusting, pitting, and tarnishing).

Condition of the seaward end anchorage

138. This end of the beam was protected by an epoxy concrete end cap over an external anchorage. The anchor consisted of a funnel housing, a 3/4-in.-thick steel plate, four washers, and a posttensioning bolt around the bar. The funnel housing was free of rust but heavily tarnished. There were small amounts of rust at both the landward and seaward funnel housings where the housing met the metal conduit, but this rust was very light. The end anchorage itself was lightly to moderately rusted. Starting from the inside, this face was moderately rusted. The

rust was more concentrated near the edges of the plate than at the center near the housing; however, the edges of this plate were free of rust. The outside face of the plate (Photo 61) was lightly rusted at the top and free of rust at the bottom. All areas were moderately tarnished; the bolt, washers, and end of the rod exposed at the seaward end were all completely free of rust and only lightly tarnished.

PART IV: SUMMARY OF OBSERVATIONS AND TESTS

Ultimate Tensile Strength and Elastic Properties of the Strands

139. Each strand of prestressing steel was analyzed by tension testing methods to determine its ultimate tensile strength, total elongation, and stress-strain properties. The tests were conducted in general accordance with the applicable portions of ASTM Designation A 370-68[5] for testing, and the results were compared with ASTM Designation A 421-59T, which was the specification that was current at the time the steel was manufactured. Structural testing results are presented in Table 5.

140. As preparation for testing, each strand was scraped and sanded to remove all the products of corrosion and then measured to determine the diameter. Measurements were taken at 2-in. intervals for approximately 12 in. on each end of the strand, and then measurements were taken at 6-in. intervals on the remainder of the strand. For structural testing, three 12-in. segments of each strand were used, two of which were the 12-in. sections at each end of the strand. The third segment was cut from the remaining part of the strand where the minimum diameter was found. The data on the strand diameters are presented in Table 7.

141. Each strand was tested in tension to ultimate load. A load-deflection curve for each strand was also made. Representative stress-strain curves for the steel strands are found in Appendix A, Plates A5-A7.

Properties of the Grout

Grout density test

142. Nine samples of grout from each metal conduit, three from each end of the beam and three from the middle, were analyzed to determine the density of the grout. The sample densities were measured,

and results are presented in Table 8.

143. The densities of the grouts ranged from 118.20 lb/ft^3 for beam 11 to 125.82 lb/ft^3 for beam 6. This is a normal range for pressure-pumped grout. With the exception of the few areas where the grout contained bleed water and air voids, this grout was essentially sound and of moderate density.

pH of the grout

144. Samples of grout were taken from the landward end, midsection, and seaward end of the conduits of seven of the eight beams tested (beams 1, 3, 6, 9, 11, 15, and 19). These samples were pulverized and placed in distilled water for pH tests. The results of these tests are presented in Table 9. All the samples gave pH readings between 12.13 and 12.90, the lowest being from beam 19 and the highest from beam 3. These readings are all in the normal range of grout, which is in the neighborhood of 12.50.[6] Since sodium chloride would tend to lower the pH of portland cement and water, it was felt that any concentration of chlorides in the grout would be indicated by a lower than normal pH reading.

Summary of Strand Corrosion

145. Every strand that was examined during the testing period was found to be covered with different amounts and different kinds of corrosion. The intensity and quantity of these products have been cataloged in paragraphs 36-138. The degree and trend of rusting on the strands in this investigation indicated areas of heavy rusting and pitting and areas in which corrosion did not predominate. In the following paragraphs, the trends of each beam are summarized in accordance with data in Table 10.

146. The landward end of beam 3 showed that rust increased from light to heavy as it proceeded inward from the anchorage. The pitting was moderate to heavy and was heaviest on strands 1-6.

147. Unlike the landward end of beam 3, the seaward end did not exhibit any rusting pattern. The overall rusting of this end was

moderate; pitting was moderate to heavy, the heaviest concentrations being on strands 1-6, 10, and 12. The midsection of this beam was moderately rusted, with strands 9-12 heavily rusted at the landward end of the section. There was no orderly pattern of rusting. This beam was prepared for structural testing before tarnishing degrees could be obtained.

148. The single rod of beam 9 was lightly rusted. The heaviest rusting, which was moderate, occurred at the seaward end. Over the entire rod, the pitting and tarnishing were moderate.

149. Beam 13, the beam that was not grouted but covered with grease, showed the heaviest rusting at the landward end. Proceeding in from the landward end, the rust decreased from heavy to light. Most of the pitting and tarnishing was light, but strands 6-8 showed moderate amounts of both.

150. At the seaward end, the rusting showed a decreasing trend as it moved away from the end anchorage. The rusting was less severe than that at the landward end for all cases. The pitting was light on most of the strands as was the tarnishing, but no pattern was noted in its occurrence.

151. Most of the grease remained on the strands over the midsection of the beam. Here, the majority of rust was moderate, and the tarnishing and pitting were light.

152. At the landward end of beam 15, the rust started moderately. Further inward from the anchorage, it increased, was heaviest at about 14 in., and then decreased again, becoming light toward the center. The behavior of the pitting followed that of the rust, and the tarnish was essentially heavy at the ends and moderate in the middle.

153. At the seaward end, the rusting was light over all the strands. The pitting was light, and the tarnishing was moderate. Neither rusting, pitting, nor tarnishing showed any trend toward increasing or decreasing. The midportions of the strands were very similar to the seaward ends. The rusting and pitting were light, and the tarnishing was moderate over the entire surface.

154. For the landward end of beam 19, the rusting exhibited no

pattern. Most of the strands were lightly rusted, particularly strands 6-9, 11, and 12. Rusting of the lower numbered strands was light at the landward end and moderate farther away from the end. The pitting was moderate for the lower numbered strands and light for the higher numbered ones. The tarnishing was moderate throughout the entire end.

155. At the seaward end, the rusting was basically light over the 32 in. The pitting was moderate in the lower numbered bars and light in the higher numbered ones. The tarnishing on the strands at this end was moderate.

156. The analysis of corrosion to the strands in the second investigation produced results in agreement with those in the first investigation. The strands were all rusted, pitted, and tarnished to varying degrees, and the severity of strand corrosion exhibited no pattern. At the landward end of beam 1, the rusting was moderate over most of the end, and the pitting and tarnishing were heavy over the whole end. There seemed to be less pitting and tarnishing on strands 10-12 than on the rest of the strands.

157. At the seaward end of the beam, the rusting changed from light to moderate at approximately 12 in. from the end. The pitting and tarnishing were heavy over the whole end except for a few strands that had only moderate pitting and tarnishing. The rusting and pitting at the midsection of the beam were moderate, with the pitting and tarnishing on strands 1-3 heavy. The tarnishing on the rest of the strands varied from moderate to heavy.

158. The analysis of beam 6 was similar to that of beam 19. At the landward end, the rusting was moderate over the entire end. On this end of the strands, the pitting was basically moderate and the tarnishing basically heavy. For the seaward end, the summary of strand corrosion was more ordered. The rusting was light on the first 13 in. of the strands and then became moderate over the rest of the end. Similarly, the pitting progressed from light to moderate, and the tarnishing was basically heavy.

159. The midsection was moderately rusted over the whole section. The pitting ranged from light to heavy with no specific trends,

and the tarnishing was moderate on the higher numbered strands and heavy on the lower numbered ones.

160. The single rod of beam 11 was moderately rusted, pitted, and tarnished over the entire beam. The only exception to this was the heavy pitting and tarnishing at the landward end from 0 to 22 in.

161. It should be reemphasized here that the classifications light, moderate, and heavy describe percentages of surface area covered and <u>not</u> depth of corrosion. In this study, the strands for which the corrosion was labeled heavy did not have deep corrosion and deterioration of the metal, with the exception of one end of one beam.

162. The analysis of the strands revealed that water, oxygen, and a condition of the surface of the steel needed to destroy the passivating film all existed at the surface of the steel. These conditions are all necessary to cause rusting. The rust that was found on the strands was not concentrated in any one area of the conduit, nor was the severity of the corrosion greater in some areas than in others. This observation can be made regarding any of the seven beams that had grouted tendons. The only beam in which the severity of the corrosion was greater at the ends was the beam containing a paper conduit filled with grease.

163. During the analysis of the rust on the strands, it became apparent that wherever two or more strands of posttensioning wire were touching or where a strand touched the metal conduit, the area was heavily rusted. These heavily rusted areas were approximately as long as the two areas which were in contact, and they extended about 1/8 in. to both sides of the contact points. These areas were heavily rusted regardless of the amount of corrosion in the adjacent areas.

164. Based on the conditions present in this study, the most probable explanation for this contact rusting is the production of electrolytic currents between areas of high and low salt concentrations.[7] Within the conduit the concentration of salt in the grout was low; also, less water and air were present, and thus fewer hydrogen and oxygen ions. In the concrete surrounding the conduit, the salt concentration was high, and the hydrogen and oxygen ions were more numerous due to the availability of water and air. With the electrolytic current

flowing, the steel inside the conduit became anodic, releasing ferrous ions and depositing hydrogen ions at the cathode. The buildup of hydrogen ions at the cathode has a tendency to slow the reaction to a stop; however, if there is an abundance of oxygen ions at the cathode, they will demand the hydrogen and allow the deposition of further hydrogen ions to continue the galvanic reaction.

Chloride Penetration Analysis of Concrete and Grout

165. One of the main objectives in the second investigation was to provide chloride penetration information that was neglected in the first investigation. In both investigations, information regarding the chloride content of the grout in the conduits was obtained. These analyses showed that the chloride content of the grout was less than 0.02 percent, which was not sufficient to cause serious corrosive damage. In the second investigation, cross-sectional analyses of the concrete were conducted to determine the depth and percentage of chlorides. The penetration of chlorides in this study was a function of the transportive medium (in this case, water), the absorption rate of the concrete, and the depth through which the chlorides needed to penetrate. Plate A8 shows the results of plots of chloride content versus depth of penetration from the surface. All the graphs show the least amount of chloride content close to the center line of the beam. Under normal circumstances, the chloride concentration would be heaviest at the surface and lightest at the center or farthest from the surface. All the graphs show this general tendency although they do not all have the characteristic curved shape shown in 11-5S. There are two types of graphs, one for 10-in.-wide and one for 5-in.-wide cross sections. The 10-in.-wide cross sections were taken near the ends of the beams where the cross sections were thick and as a result show lower total chloride percentages at the center line than do the inner cross sections that were taken from the webs of the beams and are only 5 in. wide. At the center line, the chloride contents of the 10-in. cross sections were as low as 0.05 and as high as 0.15 percent. In the 5-in.-wide cross

sections, the chlorides were higher and ranged from about 0.11 to 0.19 percent.

166. Samples of the grout from beams in both investigations were also analyzed for chloride content. In both series of tests, the total chlorides from all the samples tested were less than 0.02 percent by weight of grout. This indicated only trace amounts of chlorides within the grout, while adjacent to the outsides of the conduits the amounts were as high as 0.19 percent. The concrete beams contained more than 0.19 percent chlorides nearer the surfaces but not in the vicinity of the conduits.

End Anchorage Analysis

167. In this testing program, 12 types of end anchorage protection were presented to cover four types of end anchorages. These 12 types were divided into two types of applications, external end caps and flush end plugs, and the materials varied from air-entrained portland cement concrete to epoxy concrete to sand-cement mortar. Tables 1-4 describe the materials, posttensioning systems, and end protections used in the program.

168. Throughout the testing period, the condition of each end anchorage protection was visually inspected either annually or biannually at the Treat Island exposure station. The condition of each protective cap or plug was adjudged by a panel of observers and given a numerical rating to describe its visual condition. The tabulation below gives the average condition of each end protection type for various years throughout the study. The averages are the numerical averages of all the ends of each specific type. It should be noted that those numbered averages that decrease with increasing time do not indicate that the condition of the end anchorages improved with time but that the numerical average was taken over the number of beam ends that still remained at Treat Island. A rating of 0 indicates perfect condition, while a rating of 28 is equal to complete failure of the end protection.

Type of End Protection	No. of Beam Ends Used	Average Condition at Indicated Time and After Indicated No. of Cycles					
		0 Cycles 1961	330 Cycles 1964	623 Cycles 1966	1118 Cycles 1969	1597 Cycles 1972	1985 Cycles 1975
Flush (1)	2	0	1	2	0	2	3†
Flush (6)	2	0	0	0	0	0	0
Flush (7)	2	0	2	2	4	4	1†
Flush (9)	2	0	0	2	0	0	2†
External (1)	4	0	7	11*	13*	16**	--†
External (2)	4	0	10	11	14	10	12
External (3)	4	0	10	10*	14*	16**	--†
External (4)	4	0	11	13	15	12	13
External (5)	4	0	3	2	10*	10*	--†
External (6)	4	0	9	9*	12*	14*	--†
External (7)	4	0	1	1	4	4	3††
External (8)	4	0	1	4	4	4	7††
Total	40						

* One end protection has failed.
** Two end protections have failed.
† Beams returned to the laboratory.
†† Data based on number of beam ends remaining after test beams were returned to the laboratory.

169. *Based on the visual inspections*, after 14 years all the flush anchorage protections had numerical ratings of 4 or less, while only two of the eight external anchorage caps had ratings as low as 4, with the rest rated 10-16. The asterisks indicate the number of end anchorage protections of that particular kind that received a rating of 28, which indicates complete failure.

170. Of the four flush types, the best ratings were given to flush (6), which was an air-entrained concrete plug bonded to the beam by an epoxy adhesive, and to flush (9), which was a sand-cement mortar used as an end plug with a small amount of aluminum powder to retard shrinkage. The two external protective caps that weathered so well were external (7) and external (8), both of which were epoxy concrete end caps. These caps essentially had their cement replaced by epoxy and had the following characteristics:

Cement	Max Size Aggregate in.	Mixture Proportions by Weight Epoxy Binder:Sand:Coarse Aggregate	Compressive Strength at 28 Days, psi
None	3/4	2.83:7.00:10.00	9,320-11,320

Their portland cement counterparts, external (3) and external (4), had ratings of 16 and 12, respectively.

Evaluation of External and Internal End Anchorage Protection

171. The eight beams of the two investigations had 16 end anchorage protections, 13 of which were external end caps and 3 of which were flush end plugs. All the flush anchorage plugs were returned to the WES in good condition with average visual evaluations of 4 or less. The anchorage plug that had the best visual evaluation (rating = 0) also had the best rating of protection for the end anchorage; flush (9) had an end anchorage that was completely free of rust. The remaining two flush end anchorage plugs, flush (1) and (7), both of which were given low ratings in the visual evaluations, had moderate to heavy corrosion on the end anchorages.

172. A description and analysis of the four types of end preparation used for the joints between the beams and the 13 external end caps follow. Three joints were prepared by bush hammering the surface of the joint at 32-33 days age to roughen the joint before placement of the end cap. Of these three joints, two were still intact at the end of the study period. One of these joints (at the seaward end of beam 13) had a crack between the cap and the beam (see Appendix B). The anchorages beneath these caps were, on the whole, moderately to heavily corroded. Four of the joints were prepared by the use of a retarding agent. The inside surface of the form was coated with this retarder, and the concrete was placed against this surface. At three days age, the forms were stripped, and the retarded surface was scrubbed to remove the soft cement surface from the end of the beam, exposing some of the aggregate and producing a roughened surface. At the end of the study period, three of these joints were intact. The anchorages beneath these caps were

relatively heavily corroded, with the heaviest corrosion on the landward end anchorage of beam 19. Two of the joints were treated with an epoxy adhesive by coating the surface of the joint with the epoxy prior to casting the protective end cap over the joint, and of these two, one half of one remained intact. Both of these end anchorages were heavily corroded. Two of the joints received no preparatory treatment, and both of these were still intact, one of which (at the landward end of beam 13) was cracked between the cap and the beam. The anchorages beneath these caps were moderately corroded (landward end of beam 13) and free from corrosion (seaward end of beam 3). The two epoxy concrete end protective caps were put onto a beam surface that was sandblasted and primed. Both of these were assigned a visual rating of 4, and the inspection of the end anchorage revealed either no corrosion or very light to moderate corrosion.

173. It appears from the preceding paragraphs that the visual evaluation ratings given to the end caps and plugs, in the majority of cases, reflected the conditions of the end anchorages that the caps and plugs protected. In only two instances were there discrepancies between the anchorage corrosion and the visual ratings. The landward end of beam 1 was protected by flush (1) and was found to have heavy rust on the strands of the anchorage. In contrast, the seaward end of beam 3 was protected by external (1), which received a visual rating of 16, and its end anchorage was free from rust. These disparities are due to the fact that the visual ratings are averages of all the end protections of a particular type and do not reflect the condition of just one end cap.

174. The heaviest end anchorage corrosion was on beams 9 and 19. Beam 9 had heavy corrosion at the landward end due to the fact that the end cap was missing when the beam was delivered to the WES, and beam 19 had very heavy corrosion and deterioration on both ends due to the absence of both end caps.

175. The edges of the steel end plates were all rusted close to the exposed face, and the corrosion became lighter as it extended farther into the beam. It seems that the passivating coat that protected

the steel from corrosion was destroyed on one face of the plate but not on the opposite face, thereby indicating the outside face to be anodic and the inside cathodic.

176. Part of the purpose of this investigation was to evaluate the abilities of the different end anchorages to prevent seepage into the conduit. It was assumed that seepage will be greatest through the ends of the anchorages because these points provide the least amount of protection; that is, the grout is the only medium that must be penetrated by the moisture and oxygen, which can travel along the steel strands that are exposed through the end anchorage.

177. Part of the corrosion process involves the combination of free electrons with hydrogen ions in either water or acid substances in the water to form neutral hydrogen atoms.[8] Therefore, the end anchorage that allowed the least amount of seepage would be the system that had the least amount of corrosion at or near the ends of the strands.

178. Comparison of the results presented in Table 10 shows that beam 19 had the lightest amount of corrosion at the ends of the strands, followed by beams 15, 3, 6, 1, 9, 11, and 13, respectively. These results were obtained by determining the beam with the largest percentage of its strands only lightly corroded near the ends. For example, beam 19 had 11 of 12 strands, or 91.6 percent, lightly corroded at the landward end, and 8 of 12 strands, or 66.7 percent, at the seaward end only lightly corroded.

179. Beam 13, which had the conduit filled with grease, had the worst corrosion at the ends. At the landward end of the strands on this beam, 87.5 percent of the strands were heavily corroded, and at the seaward end, 62.5 percent were moderately corroded. Just inside the landward end anchorage plate the diameters of the strands were all slightly smaller than the diameters of other parts of the strands, and the cross section of one strand was so reduced that it had broken, presumably during structural testing (Photo 11). The combination of type of end anchorage of this beam and the fact that the conduit was a paper product explains the large amount of corrosion due to seepage through the anchorage and conduit.

180. The construction of the end anchor system of beam 19 apparently aided in the lack of heavy corrosion to the strands. Photo 29 shows the landward end anchorage system, which consists of two rings. The inside ring contains the strands that have button heads on them, and the outer ring is rotated to apply the posttension force to the inner ring. The strands only come in contact with the outside environment through the holes beneath the button heads. The grout is pumped through the center of the inside ring, and water and oxygen must penetrate this grout to corrode the steel. Water entering the system along the strands is retarded due to the contact pressure of the button head against the inner steel ring at the end of the strand. The seaward end anchorage system is the same as that shown in Photo 37 with one exception, i.e., the strands are tensioned from the landward end, and no threaded ring is at this end.

181. Unlike the landward end anchorage system of beam 19, systems used in beams 13 and 15 had no barrier to moisture entering along the strands except the concrete protective cap that is cast over the end anchorage system. As shown in Figure 17, the strands enter the beam through the large rectangular plate. There is no pressure fit of the button head at this point. Consequently, water and oxygen can travel along the strands and into the conduit. Photos 11 and 14 show the inside surface of this type anchor plate with the corrosion around the holes. This was the only instance in which the inside face of an anchor plate was corroded in the middle.

Figure 17. Strands entering beam through the rectangular plate

X-Ray Diffraction (XRD) Analysis

182. The iron oxide scrapings from each strand were taken to be examined by XRD. Also, the creamy-colored pieces of grout from beam 15

were analyzed to determine their chemical composition. Table 11 presents results of the analyses. Both alpha iron and magnetite were found in every beam. These are not rust products but products of the iron that was scraped from the strand along with the rust. Goethite (FeO(OH)) was found on every sample tested; this is hydrated iron oxide that is the main product of rusting. Along with these iron products, there were X-ray peaks that indicated the presence of grout and quartz.

183. Analysis of the cream-colored grout sample referred to in paragraph 80 revealed that the grout had high concentrations of calcite. This was probably produced by water reacting with calcium hydroxide formed during hydration of the cement and its resulting carbonation to form calcium carbonate.[9]

184. Aluminum chloride has its strongest peak at 246 Å. Iron oxide samples from beam 3 contained minerals that caused a peak at 246 Å. It was concluded that this peak was a result of chlorides present in the beam and aluminum added to the grout to prevent shrinkage.

PART V: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

185. The following paragraphs present the conclusions that can be drawn based on the results of the testing.

186. In all, eight posttensioned beams were returned to the WES from Treat Island. Of the eight, beams 3, 9, 13, 15, and 19 were subjected to 1737 cycles of freezing and thawing over a period of 12 winters, and beams 1, 6, and 11 were subjected to 1873 cycles of freezing and thawing over a period of 13 winters. From the photographic evaluations of the beams as they were received in the laboratory (Figures 3, 5, 6, 8, 10, 13, 15, and 16) and the respective paragraphs describing their conditions, it is concluded that there was heavy spalling of the concrete that protected the longitudinal conventional reinforcing. This resulted in the steel being directly exposed to the corrosive marine atmosphere and thus being further deteriorated by its effects. The heavy spalling was due to the fact that the longitudinal reinforcement was only protected by a 3/4-in. cover of concrete. Therefore, a 3/4-in. cover is determined to be inadequate to protect steel from the exposure to seawater and the action of freezing and thawing.

187. In the structural testing of all eight beams, only one strand broke during testing (strand 3 of beam 13), and subsequent to opening the beams, only five pieces of strand were found that did not conform to ASTM ultimate stress requirements.[5] Only 17 pieces of strand failed to meet ASTM requirements for total elongation under load and elongation at 1 percent of load, and of these 17, eight were from the landward end of beam 13 (Table 5). These failures account for only 22 out of 157 tests. It is therefore concluded that the steel strands were not structurally damaged by exposure to severe environments of freezing and thawing in a saline surrounding when the posttensioning conduit was filled with a grout mixture to protect the strands.

188. The steel of beam 13 was protected by a paper conduit filled with grease. The results of observation and testing showed that the

landward end of this beam received the heaviest amount of corrosion and deterioration of the strand diameter. Also, when the conduit was opened, several spots on the paper conduit were torn, and many areas of the strands were either not covered with grease or were covered with dried-out grease. In these areas of this beam, the strands were the most corroded of all the strands tested. From this and the results of structural testing presented in Table 5, it is concluded that the paper conduit filled with grease provided the strands with the least amount of protection from corrosion during the life of the beam.

189. Each strand of each beam was rusted to some degree. Paragraphs 36-138 and Table 10 indicate that the corrosion was not confined to the ends of the strands on any beam. Neither was the corrosion concentrated at any one spot but was continuously spread over the entire length of the strands. Only in the case of beam 13 was there more corrosion associated with the ends than the middle, and this beam was protected by the grease-filled conduit. Should the corrosion have been due to seepage of water and oxygen through the ends of the beam, then the rust would have been heaviest in these areas. It is concluded that seepage through the ends of the beam was not responsible for all the oxygen and water that reached the strands and caused corrosion. Furthermore, since rust was found in the joints of the individual sections of the conduit, the ingress of water and oxygen occurred here also.

190. The testing and evaluation of the end protective caps and plugs yielded the following conclusions. The best protection to the end anchorage was provided by the epoxy end caps. When the end anchorages were sealed inside the epoxy caps, they were not subjected to air or water and could not be rusted. These end caps also produced the best results in the visual evaluation of external end caps. Epoxy concrete end caps were the most resistive to the effects of freeze-thaw weathering.

191. All the flush anchorage plugs gave excellent resistance to weathering. These plugs were only exposed to the atmosphere at the ends of the beams. They were surrounded by the beams themselves on all sides. Beneath two of the three flush anchorage end plugs, the anchorages were rusted and corroded. One of these was an epoxy concrete plug that had

poor consolidation around the end anchorage. From this, it is concluded that since the flush anchorage plugs were surrounded by the concrete of the beams, and since the concrete came in contact with the end anchorage where the plug stopped, the flush anchorage plugs protected the anchorage only as well as the concrete itself did.

192. Evaluation of the four methods of joint preparation (bush hammering, retarding agent, epoxy coating, and no preparation at all) were made on all the beams that had portland cement concrete end caps protecting external anchorages. This included 24 joints of the 40 joints in the 20 beams. Sixteen of these joints (four each of the four methods) had no reinforcement between the beam and the end cap, and eight joints (four each from the bush hammered preparation and no preparation methods) had reinforcing bars to aid in the maintenance of the end caps. Of the two types of construction, with reinforcement and without reinforcement, there were no end cap failures with the reinforcement, and there were 8 failures without reinforcement. Also, with respect to the durability of the method of joint preparation against failure by freezing and thawing, the retarding agent produced fewer end cap failures than the remaining methods of protection.

193. The end anchorages were, in most cases, more deteriorated than the strands that they protected. Also, the landward end anchorage plates were more corroded than the seaward end anchorages, indicating that the environment to which the anchorage plates were subjected was more severe than that to which the strands were subjected and that the anchorage plates afforded good protection from the seepage of seawater. It is concluded from the condition of the strands that the posttensioning system of beam 19 provided the best seepage protection and that the system of beam 13, the worst protection.

Bond between grout and steel

194. The bond characteristics of the beams were noted throughout the tests. When the beams were opened after being failed, the bond between the grout and the steel was found to be good. It was observed that the pieces of grout stuck to the strands of steel even though they were cracked during the failure of the beam and the opening of the

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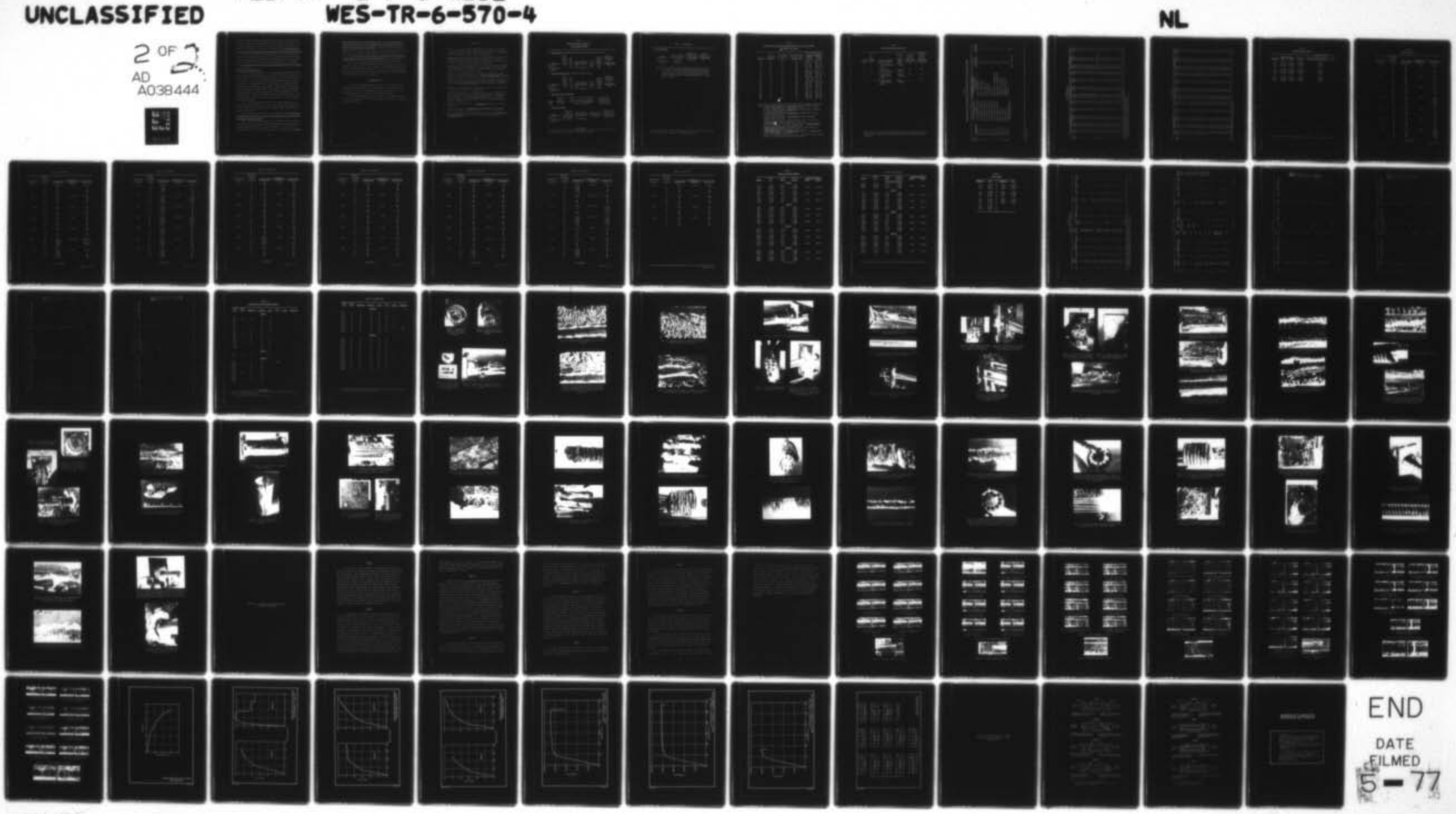

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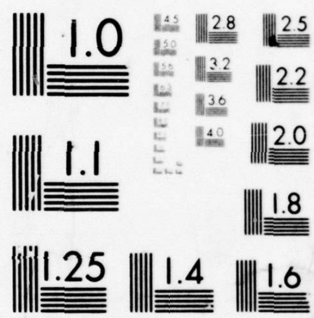

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conduit. When the grout was removed, the rust spots on the interface between it and the steel matched the amount of rust on the steel. Also, the heavier amounts of pitting on the steel provided better bond between the two materials. Thus, it is concluded that the bond between the grout and steel was improved by the presence of the rust and pitting.

195. The remaining posttensioning forces in the steel were held by the bond between the steel and the grout and were not released until the conduit was cut, relieving the constraining forces of the conduit. Since the conduit of beam 13 was filled with grease, it is concluded that no residual forces were held in the posttensioning steel of beam 13.

Chemical analysis of
grout and corrosion products

196. The chemical analysis of the grout samples taken from each conduit within the beam revealed less than 0.02 percent chlorides in the chloride tests. This test indicated the presence of only trace amounts of chlorides. The tests for sodium and potassium showed 0.07 percent sodium and 0.15 percent potassium. These amounts of alkalies totaled to constitute 0.1687 percent soda, which is well within the expected range for type III portland cement[10] and did not indicate the presence of excess sodium or potassium chloride. The grout samples were also checked for pH. The results showed that the pH of the grout was in the vicinity of 12.5, which is normal for grout that has very small amounts of chlorides present.

197. X-ray diffraction analysis of the rust scraped from the strands indicated the presence of alpha iron, goethite, and magnetite. No iron chloride was reported, and the analysis showed small amounts of aluminum chloride.

198. From the above results, it is concluded that there were not enough chlorides present in the grout to be the main factor that caused the corrosion on the strands.

199. Since there was rusting of the strands in all the beams, it is certain that water, oxygen, and some mechanism to destroy the passivating protective film on the steel were present. Also, since the chloride content of the grout was so low, it is concluded that the water

that caused corrosion to the strands was due to excess mixing water present in the grout when it was pumped into the conduit and not to seawater that seeped into the conduit. Further, since some method of reducing the passivating film of the steel was necessary, and since this could not be attributed to the presence of salts in the grout, it is concluded that a galvanic current was set up between the two different concentrations of salt in the concrete and grout, thus producing the mechanism necessary to destroy the passivating film on the steel.

200. Since there was evidence of strand-to-strand and strand-to-conduit contact, and since in most cases the strands were closer to one side of the conduit than to the other, there is a need for some type of noncorrosive spacer that will effectively separate the strands and keep them away from the side of the conduit.

Recommendations

201. From the material and data gathered in the posttensioned concrete beam investigation[1,2] and the results of this phase of the investigation, it is considered that further active study of the post-tensioned beams would not yield more pertinent information.

202. The remaining beams should be left at the exposure station to continue weathering and to provide specimens for future investigations should they be needed.

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Table 1

Mixtures Used to Fabricate

Posttensioned Beams

A. Beams Proper (excluding the grout and anchorage protection)

Cement	Max Size Aggregate in.	Air Content %	Water-Cement Ratio (by Wt)*	Slump in.	Cement Factor bags*/cu yd	Nominal Compressive Strength psi (28 Days Age)
Type III (high-early-strength)	3/4	4.0-5.0	0.52 (5.85 gal/bag)	1-1/2 to 2	5.98-6.05	6000

B. Anchorage Protection (excluding epoxy mixture)

Cement	Max Size Aggregate in.	Air Content %	Water-Cement Ratio (by Wt)*	Slump in.	Cement Factor bags*/cu yd	Nominal Compressive Strength psi (28 Days Age)
Type III (high-early-strength)	3/4	3.5-5.0	0.80 (9.03 gal/bag)	1-1/4 to 2	3.90-3.96	3000

C. Epoxy Concrete Protection

Cement	Max Size Aggregate, in.	Mixture Proportions (by Wt), Epoxy Binder:Sand:Coarse Aggregate	Compressive Strength, psi (28 Days Age)
None	3/4	2.83:7.00:10.00	9,320-11,320

D. Mortar Mixtures

Cement	Max Size Aggregate, in.	Water-Cement Ratio (by Wt)*	Cement Factor bags*/cu yd	Compressive Strength, psi (28 Days Age)
Type III (high-early-strength)	100% passing No. 4 sieve	0.44 (4.95 gal/bag)	10.90	7710-7800

(Continued)

* One bag = 94 lb of cement = 0.4535924 kg (mass).

Table 1 (Concluded)

E. Grout Mixtures

Cement	Water Cement Ratio (by Wt)*	Compressive Strength, psi (7 Days Age)	Linear Expansion, % (3 Days Age)
Type III (high-early-strength)	0.40-0.49 (4.51-5.53 gal/bag)	3740-6430	0-7

Note: All grouts were neat cement grouts except that used for beam 14, which was a natural sand grout (100 percent passing No. 30 sieve). All of the grouts contained a small amount of aluminum powder (1 to 3 g per bag of cement).

* One bag = 94 lb of cement = 0.4535924 kg (mass).

Table 2

General Information, Posttensioned Beams at Treat Island

(Installed June 1961)

Beam No.	Post-tensioning System	Eccentricity of Tendon in.	Estimated Final Posttensioning Force, tons	Type of End Protection (See Note) Landward End	Seaward End
1*	A	0	23	Flush (1)	Ext (5)
2	A	0	23	Ext (4)	Ext (2)
3*	A	3	23	Ext (3)	Ext (1)
4	A	2	23	Ext (7)	Flush (7)
5	A	2	23	Ext (6)	Flush (6)
6*	A	1	23	Flush (9)	Ext (8)
7	B	0	26	Ext (1)	Flush (1)
8	B	2	26	Ext (2)	Ext (4)
9*	B	3	26	Ext (3)	Ext (5)
10	B	3	26	Flush (6)	Ext (6)
11*	B	1	26	Flush (7)	Ext (7)
12	B	1	26	Ext (8)	Flush (9)
13*	C	0	30	Ext (1)	Ext (3)
14	C	1	30	Ext (2)	Ext (4)
15*	C	3	30	Ext (5)	Ext (6)
16	C	2	30	Ext (7)	Ext (8)
17	D	3	42	Ext (1)	Ext (3)
18	D	0	42	Ext (4)	Ext (2)
19*	D	2	42	Ext (5)	Ext (6)
20	D	1	42	Ext (8)	Ext (7)

Note: Concrete placed against a cold joint with no surface treatment and no reinforcement (Ext (1) and Flush (1)).

Concrete placed against a cold joint with no surface treatment but with reinforcement (Ext (2)).

Concrete placed against a bush-hammered surface and with no reinforcement (Ext (3)).

Concrete placed against a bush-hammered surface but with reinforcement (Ext (4)).

Concrete placed against a surface that had been treated with a retarding agent and no reinforcement (Ext (5)).

Concrete bonded to the ends of the beam with an epoxy adhesive and no reinforcement (Ext (6) and Flush (6)).

Epoxy concrete without reinforcement (Ext (7) and Flush (7)).

Epoxy concrete with reinforcement (Ext (8)).

Sand-cement mortar with aluminum powder additive, comparatively dry and well tamped (Flush (9)).

* Beams were examined in the laboratory. The tendon in beam 13 was found to be unbonded and coated (not grouted).

Table 3

Posttensioning Systems Used

System	No. of Beams Tested	Type of Tendon	Method of Anchoring	Initial Posttensioning Force, tons	Estimated Final Posttensioning Force, tons
A	3	12 steel wires (each 0.196-in. diam)	Wedge action	42	23
B	2	1 steel bar (7/8-in. diam)	Direct bearing	35	26
C	2*	8 steel wires (each 1/4-in. diam)	Direct bearing	35	30
D	1	12 steel wires (each 1/4-in. diam)	Direct bearing	50	42

* One of these tendons was unbonded and coated with a mineral grease (beam 13).

Table 4

Twelve Types of End Anchorage Protection Used for Posttensioned Beams

		End Anchorage Protection			
Type No.	Designation*	Protective Material Used	Beam End Surface Treatment	Steel Reinforcement	No. of Beam Ends
1	Ext (1)	Air-entrained concrete	None, cold joint	No	4
2	Flush (1)	Air-entrained concrete	None, cold joint	No	2
3	Ext (2)	Air-entrained concrete	None, cold joint	Yes	4
4	Ext (3)	Air-entrained concrete	Bush-hammered	No	4
5	Ext (4)	Air-entrained concrete	Bush-hammered	Yes	4
6	Ext (5)	Air-entrained concrete	Retarded	No	4
7	Ext (6)	Air-entrained concrete	Epoxy-coated (sandblasted)	No	4
8	Flush (6)	Air-entrained concrete	Epoxy-coated (sandblasted)	No	2
9	Ext (7)	Epoxy concrete	Sandblast and primer	No	4
10	Flush (7)	Epoxy concrete	Sandblast and primer	No	2
11	Ext (8)	Epoxy concrete	Sandblast and primer	Yes	4
12	Flush (9)	Sand-cement mortar (with aluminum powder)	Sandblasted	No	2
				Total beam ends	40

* See Table 2.

Table 5

Structural Testing Data

Beam-Strand	Landward End Ultimate Load lb	Ultimate Stress psi	Load at 1% Elongation lb	Total Elongation %	Midsection Ultimate Load lb	Ultimate Stress psi	Load at 1% Elongation lb	Total Elongation %	Seaward End Ultimate Load lb	Ultimate Stress psi	Load at 1% Elongation lb	Total Elongation %
3-1	7,480	261,063	6,150	4.96	7,495	261,587	6,600	6.06	7,425	259,143	6,525	4.97
2	7,500	253,728	6,300	4.39	7,575	256,265	6,770	6.31	7,570	256,096	6,810	5.87
3	7,575	253,644	7,000	4.60	7,635	255,653	7,060	5.68	7,565	253,309	6,910	4.93
4	7,520	254,405	6,820	5.10	7,630	258,126	7,000	6.61	7,490	250,797	6,820	4.29
5	7,430	259,318	6,790	5.53	7,500	261,761	6,800	6.36	7,460	260,365	6,720	5.60
6	7,305	247,131*	6,720	5.64	7,325	247,808*	6,835	4.84	7,305	247,131*	6,695	6.40
7	7,445	259,841	6,790	5.66	7,475	260,889	6,810	4.74	7,275	253,908	6,510	3.69†
8	7,565	264,030	6,890	5.24	7,460	260,365	6,790	4.62	7,425	259,143	6,700	5.50
9	7,880	263,856	7,250	5.24	7,710	258,164	7,100	6.51	7,620	255,150	6,960	4.36
10	7,565	264,030	6,800	4.25	7,420	258,969	6,780	5.95	7,405	258,445	6,670	5.28
11	7,520	262,459	6,800	5.98	7,110	248,149*	6,820	1.68†	7,425	259,143	6,730	4.83
12	7,730	258,834	7,175	5.24	7,675	256,992	7,050	6.35	7,620	.255,150	6,950	5.54
9-1	103,500	163,417	133,500	3.49	103,250	163,023	145,000	3.41	SECTION NOT TESTED			
13-1	12,025	253,003	10,845	3.50†	12,240	255,445	10,905	6.30	12,285	254,321	10,770	4.83
2	11,850	251,360	10,830	2.84†	12,135	253,254	10,650	5.42	12,360	255,874	10,620	6.66
3	11,295	241,556	10,020	2.62†	12,300	254,632	10,035	5.49	12,285	252,282	9,735††	6.09
4	11,370	239,222**	10,665	1.65†	12,345	257,637	11,025	5.71	12,285	254,321	10,560	5.31
5	11,625	248,613	10,560	2.49†	12,360	255,874	10,995	4.57	12,300	258,789	10,575	4.88
6	11,520	240,419	10,740	2.06†	12,300	254,632	10,740	5.06	12,270	254,011	10,590	5.34
7	11,955	253,588	10,815	3.46†	12,270	254,011	10,980	4.78	12,300	254,632	10,905	5.92
8	11,430	242,451	10,395	2.48†	12,315	254,942	9,630††	7.25	12,285	252,282	10,620	6.44
15-1	11,925	244,890	9,855	5.75	11,895	244,273	9,930	6.52	11,940	245,198	9,930	7.66
2	11,775	241,809	9,870	5.57	11,850	243,349	9,885	6.29	11,865	243,657	9,900	6.15
3	11,955	245,506	9,945	5.56	11,970	245,814	9,975	7.14	11,910	244,581	9,855	6.98
4	12,105	248,586	10,080	6.34	12,015	246,738	9,960	7.16	11,985	246,122	9,990	5.99

(Continued)

* Did not meet ASTM stress requirements for wedge type (WA) anchorage.
** Did not meet ASTM stress requirements for button type (BA) anchorage.
† Did not meet ASTM requirements for total elongation under load.
†† Did not meet ASTM stress requirements for elongation at 1 percent of load.

Table 5 (Concluded)

Beam-Strand	Landward End Ultimate Load lb	Landward End Ultimate Stress psi	Landward End Load at 1% Elongation lb	Landward End Total Elongation %	Midsection Ultimate Load lb	Midsection Ultimate Stress psi	Midsection Load at 1% Elongation lb	Midsection Total Elongation %	Seaward End Ultimate Load lb	Seaward End Ultimate Stress psi	Seaward End Load at 1% Elongation lb	Seaward End Total Elongation %
15-5	11,985	246,122	10,020	6.98	11,955	245,506	9,975	6.64	11,940	245,198	9,900	6.36
6	12,105	248,586	10,050	7.25	12,000	246,430	10,005	7.32	11,970	245,814	10,005	6.76
7	12,015	246,738	10,050	6.64	12,015	246,738	9,990	7.30	11,955	245,506	9,930	7.66
8	12,000	246,430	10,065	6.80	11,955	245,506	10,020	5.98	11,955	245,506	9,900	7.15
19-1	12,735	251,329	10,605	7.13	12,750	251,625	10,635	6.80	13,200	260,506	10,935	6.72
2	12,720	251,033	10,560	7.39	12,735	251,329	10,515	7.36	12,570	248,072	10,380	6.29
3	12,720	251,033	10,545	6.18	12,600	248,664	10,500	7.59	12,705	250,737	10,500	7.04
4	12,825	253,105	10,650	6.48	12,675	250,145	10,515	6.16	12,735	251,329	10,530	7.82
5	12,915	254,881	10,620	6.13	12,690	250,441	10,650	6.77	12,765	251,921	10,530	7.11
6	12,615	248,960	10,365	7.49	12,630	249,256	10,530	7.90	12,975	256,065	10,695	8.97
7	12,645	249,552	10,530	6.71	12,795	252,513	10,695	6.14	12,900	254,585	10,650	6.72
8	12,735	251,329	10,470	7.19	13,020	256,953	10,845	6.73	13,020	256,953	10,770	7.50
9	12,645	249,552	10,395	7.09	12,960	255,769	10,725	7.10	12,930	255,177	10,650	6.34
10	12,750	251,625	10,695	6.75	12,690	250.441	10,620	6.74	12,675	250,145	10,665	5.11
11	12,525	247,184	10,425	6.97	13,020	256,953	10,830	7.93	12,900	254,585	10,680	7.52
12	12,615	248,960	10,470	7.47	13,020	256,953	10,785	7.86	12,855	253,697	10,635	6.76
1-1	7,550	263,506	6,720	4.40	7,590	264,902	6,890	5.36	7,600	265.251	6,940	5.24
2	7,580	264,553	6,720	4.87	7,630	266,298	6,980	4.95	7,560	263,855	6,760	4.72
3	7,420	256,278	6,620	3.37†	7,610	265,600	7,000	5.30	7,520	262,459	6,840	5.98
4	7,390	257,922	6,680	3.00†	7,610	265,600	6,870	5.24	7,570	264,204	6,790	5.21
5	7,570	264,204	6,820	4.84	7,610	268,403	6,950	5.24	7,510	262.110	6,830	5.86
6	7,570	264,204	6,880	4.43	7,620	265,949	6,890	5.15	7,510	262.110	6,700	5.05
7	7,490	261,412	6,670	3.78†	7,600	265,251	6,900	5.04	7,540	263,157	6,800	5.68
8	7,550	263,506	6,770	5.01	7,580	264,553	6,930	4.74	7,570	264,204	6,850	4.62
9	7,690	268,392	6,990	4.09	7,580	264,553	6,910	4.60	7,580	264,553	6,800	4.10
10	7,680	268,043	7,000	5.05	7,620	265,949	6,900	5.73	7,580	264,553	6,900	4.59
11	7,610	265,600	6,940	3.93†	7,570	264,204	6,880	5.42	7,590	264,902	6,830	5.38
12	7,620	265,949	6,960	4.69	7,560	263,855	6,980	3.23†	7,580	264,553	6,870	4.76

† Did not meet ASTM requirements for total elongation under load.

Table 6

Water Content of Grout

Beam-End	Sample Weight, g Wet	Dry	Moisture Loss, g	% Water Content $\left(\frac{\text{Weight of Moisture Loss}}{\text{Weight of Wet Sample}} \times 100\right)$
1-L	15.9583	13.5418	2.4165	15.14
1-M	18.4267	15.7762	2.6505	14.38
1-S	10.6162	8.9869	1.6293	15.35
6-L	9.7091	8.1991	1.5100	15.55
6-M	16.9462	14.2036	2.7426	16.18
6-S	9.4832	8.0577	1.4255	15.03
11-L	9.1524	7.4333	1.7191	18.78
11-M	11.5868	9.6103	1.9765	17.06
11-S	9.9681	8.3144	1.6537	16.59

Table 7

Strand Diameters

Beam-Strand No.	Distance from End of Strand in.	Diameter, in.		
		Landward End	Midspan	Seaward End
3-1	2	0.191	0.191	0.191
	4	↓		↓
	6	↓		↓
	8	↓		↓
	10	↓		↓
3-2	2	0.194	0.194	0.194
	4	↓		↓
	6	↓		↓
	8	↓		↓
	10	↓		↓
3-3	2	0.195	0.195	0.195
	4	↓		↓
	6	↓		↓
	8	↓		↓
	10	↓		↓
3-4	2	0.194	0.194	0.194
	4	↓		0.195
	6	↓		0.194
	8	↓		0.194
	10	↓		0.194
3-5	2	0.191	0.191	0.191
	4	↓		↓
	6	↓		↓
	8	↓		↓
	10	↓		↓
3-6	2	0.194	0.194	0.194
	4	↓		↓
	6	↓		↓
	8	↓		↓
	10	↓		↓
3-7	2	0.191	0.191	0.191
	4	↓		0.192
	6	↓		0.191
	8	↓		0.191
	10	↓		0.191

(Continued)

Table 7 (Continued)

Beam-Strand No.	Distance from End of Strand in.	Diameter, in. Landward End	Midspan	Seaward End
3-8	2	0.191	0.191	0.191
	4			
	6			
	8			
	10			
3-9	2	0.195	0.195	0.195
	4			
	6			
	8			
	10			
3-10	2	0.191	0.191	0.191
	4			
	6			
	8			
	10			
3-11	2	0.191	0.191	0.191
	4			
	6			
	8			
	10			
3-12	2	0.195	0.195	0.195
	4			
	6			
	8			
	10			
9-1	6	0.895	0.894-0.896	Seaward end of rod bent, no reading
	12	0.896		
	18	0.898		
	24	0.895		
	30	0.896		
13-1	2	0.247	0.247	0.248
	4	0.247		
	6	0.246		
	8	0.246		
	10	0.247		

(Continued)

Table 7 (Continued)

Beam-Strand No.	Distance from End of Strand in.	Diameter, in. Landward End	Midspan	Seaward End
13-2	2	0.245	0.247	0.248
	4	0.247		
	6	0.247		
	8	0.247		
	10	0.247		
13-3	2	0.244	0.248	0.249
	4	0.247		0.249
	6	0.248		0.249
	8	0.248		0.248
	10	0.248		0.248
13-4	2	0.246	0.247-0.248	0.248
	4	0.247		
	6	0.247		
	8	0.247		
	10	0.247		
13-5	2	0.244	0.247-0.248	0.248
	4	0.246		0.246
	6	0.246		0.247
	8	0.246		0.248
	10	0.246		0.248
13-6	2	0.247	0.248	0.248
	4	0.247		
	6	0.246		
	8	0.247		
	10	0.247		
13-7	2	0.247	0.248	0.248
	4	0.247		
	6	0.247		
	8	0.245		
	10	0.246		
13-8	2	0.245	0.248	0.249
	4	0.245		
	6	0.248		
	8	0.248		
	10	0.248		

(Continued)

Table 7 (Continued)

Beam-Strand No.	Distance from End of Strand in.	Diameter, in. Landward End	Midspan	Seaward End
15-1	2	0.249	0.249	0.249
	4	↓		↓
	6			
	8			
	10			
15-2	2	0.249	0.249	0.249
	4	↓		↓
	6			
	8			
	10			
15-3	2	0.249	0.249	0.249
	4	↓		↓
	6			
	8			
	10			
15-4	2	0.249	0.249	0.249
	4	↓		↓
	6			
	8			
	10			
15-5	2	0.249	0.249	0.249
	4	↓		↓
	6			
	8			
	10			
15-6	2	0.249	0.249	0.249
	4	0.249		↓
	6	0.249		
	8	0.249		
	10	0.248		
15-7	2	0.249	0.249	0.249
	4	↓		↓
	6			
	8			
	10			

(Continued)

Table 7 (Continued)

Beam-Strand No.	Distance from End of Strand in.	Diameter, in. Landward End	Diameter, in. Midspan	Diameter, in. Seaward End
15-8	2	0.249	0.249	0.249
	4			
	6			
	8			
	10			
19-1	2	0.254	0.254	0.254
	4			
	6			
	8			
	10			
19-2	2	0.254	0.254	0.254
	4			
	6			
	8			
	10			
19-3	2	0.254	0.254	0.254
	4			
	6			
	8			
	10			
19-4	2	0.254	0.254	0.254
	4			
	6			
	8			
	10			
19-5	2	0.254	0.254	0.254
	4			
	6			
	8			
	10			
19-6	2	0.254	0.254	0.254
	4			
	6			
	8			
	10			

(Continued)

Table 7 (Continued)

Beam-Strand No.	Distance from End of Strand in.	Diameter, in.		
		Landward End	Midspan	Seaward End
19-7	2	0.254	0.254	0.254
	4			
	6			
	8			
	10			
19-8	2	0.254	0.254	0.254
	4			
	6			
	8			
	10			
19-9	2	0.254	0.254	0.254
	4			
	6			
	8			
	10			
19-10	2	0.254	0.254	0.254
	4			
	6			
	8			
	10			
19-11	2	0.254	0.254	0.254
	4			
	8			
	6			
	10			
19-12	2	0.254	0.254	0.254
	4			
	6			
	8			
	10			
1-1	2	0.191	0.191	0.191
	4	0.191		
	6	0.192		
	8	0.191		
	10	0.191		

(Continued)

Table 7 (Continued)

Beam-Strand No.	Distance from End of Strand in.	Diameter, in. Landward End	Midspan	Seaward End
1-2	2	0.192	0.191	0.191
	4	0.191		
	6	0.191		
	8	0.191		
	10	0.191		
1-3	2	0.192	0.191-0.192	0.191
	4			
	6			
	8			
	10			
1-4	2	0.191	0.191-0.192	0.191
	4			0.192
	6			0.192
	8			0.191
	10			0.191
1-5	2	0.191	0.190-0.192	0.191
	4	0.192		0.192
	6	0.192		0.191
	8	0.191		0.191
	10	0.192		0.190
1-6	2	0.191	0.191	0.191
	4			
	6			
	8			
	10			
1-7	2	0.191	0.191	0.191
	4			
	6			
	8			
	10			
1-8	2	0.192	0.191	0.191
	4	0.192		
	6	0.192		
	8	0.192		
	10	0.191		

(Continued)

(Sheet 7 of 8)

Table 7 (Concluded)

Beam-Strand No.	Distance from End of Strand in.	Diameter, in. Landward End	Midspan	Seaward End
1-9	2	0.191	0.191	0.191
	4			
	6			
	8			
	10			
1-10	2	0.191	0.191	0.191
	4			
	6			
	8			
	10			
1-11	2	0.191	0.191	0.191
	4			
	6			
	8			
	10			
1-12	2	0.191	0.191	0.191
	4			
	6			
	8			
	10			

(Sheet 8 of 8)

Table 8

Density of Grout Samples

Sample	Weight g	Volume cm3	Density g/cm3	Average Density g/cm3	Average Density lb/ft3
			Beam 3		
3L-1	27.01	13.6	1.986		
3L-2	22.73	11.8	1.926	1.957	122.19
3L-3	28.81	14.7	1.960		
3M-1	18.53	9.8	1.891		
3M-2	20.38	10.5	1.941	1.946	121.49
3M-3	16.05	8.0	2.006		
3S-1	25.20	12.9	1.953		
3S-2	15.76	8.0	1.970	1.954	122.01
3S-3	20.18	10.4	1.940		
			Beam 9		
9L-1	22.46	11.9	1.887		
9L-2	24.93	13.0	1.918	1.922	119.99
9L-3	23.73	12.1	1.961		
9M-1	30.47	15.2	2.004		
9M-2	33.57	17.3	1.940	1.959	122.30
9M-3	23.77	12.3	1.933		
9S-1	25.15	12.6	1.996		
9S-2	28.91	14.7	1.966	1.982	123.73
9S-3	31.74	16.0	1.984		
			Beam 15		
15L-1	19.13	9.9	1.932		
15L-2	17.16	8.9	1.928	1.931	120.57
15L-3	21.27	11.0	1.934		
15M-1	16.62	8.5	1.955		
15M-2	21.30	10.9	1.954	1.946	121.46
15M-3	21.59	11.2	1.928		
15S-1	19.86	10.0	1.986		
15S-2	20.55	10.9	1.886	1.934	120.74
15S-3	22.19	11.5	1.930		
			Beam 19		
19L-1	24.87	12.9	1.928		
19L-2	20.76	10.9	1.905	1.914	119.47
19L-3	22.90	12.0	1.908		
19M-1	21.02	11.0	1.911		
19M-2	26.95	14.0	1.925	1.917	119.70
19M-3	24.71	12.9	1.916		

(Continued)

Table 8 (Concluded)

Sample	Weight g	Volume cm 3	Density g/cm3	Average Density g/cm3	Average Density lb/ft3
			Beam 19 (Continued)		
19S-1	24.79	13.0	1.907		
19S-2	27.60	14.6	1.890	1.907	119.03
19S-3	23.08	12.0	1.923		
			Beam 1		
1L-1	20.40	10.3	1.981		
1L-2	21.20	11.0	1.928	1.950	121.74
1L-3	19.22	9.9	1.941		
1M-1	19.63	9.9	1.983		
1M-2	19.38	10.1	1.918	1.959	122.32
1M-3	19.97	10.1	1.977		
1S-1	19.85	10.1	1.966		
1S-2	19.73	10.8	1.828	1.923	120.07
1S-3	20.35	10.3	1.976		
			Beam 6		
6L-1	20.19	9.9	2.040		
6L-2	19.58	9.8	1.998	2.015	125.82
6L-3	19.88	9.9	2.008		
6M-1	20.40	10.5	1.942		
6M-2	20.32	10.7	1.899	1.925	120.18
6M-3	19.53	10.1	1.934		
6S-1	20.32	10.2	1.992		
6S-2	20.16	10.4	1.938	1.960	122.38
6S-3	18.52	9.4	1.949		
			Beam 11		
11L-1	20.86	11.0	1.896		
11L-2	18.55	10.0	1.855	1.893	118.20
11L-3	19.49	10.1	1.929		
11M-1	19.40	10.0	1.937		
11M-2	19.97	10.2	1.958	1.933	120.69
11M-3	20.20	10.6	1.905		
11S-1	20.51	10.6	1.935		
11S-2	19.04	9.9	1.923	1.939	121.07
11S-3	19.60	10.0	1.960		

Table 9

pH of Grout

Beam-End	pH	Beam-End	pH
1-L	12.44	11-L	12.42
1-M	12.44	11-M	12.42
1-S	12.45	11-S	12.42
3-L	12.65	15-L	12.43
3-M	12.86	15-M	12.38
3-S	12.90	15-S	12.58
6-L	12.42	19-L	12.13
6-M	12.40	19-M	12.18
6-S	12.47	19-S	12.21
9-L	12.58		
9-M	12.50		
9-S	12.61		

Table 10

Summary of Corrosion Intensities

Strand	Distance from Landward End, in.	Landward End Rusting	Landward End Pitting	Landward End Tarnishing*	Distance from Ends,** in.	Midsection Rusting	Midsection Pitting	Midsection Tarnishing*	Distance from Seaward End, in.	Seaward End Rusting	Seaward End Pitting	Seaward End Tarnishing*
						Beam 3						
3-1	0-2	L	M	--	32→57	M	M	--	0-18	M	H	--
	2-32	M	H	--	39←32	H	H	--	18-32	H	H	--
3-2	0-2	M	H	--	32→48	M	H	--	0-12	M	H	--
	2-32	M	H	--	48←32	M	M	--	12-32	M	H	--
3-3	0-8	L	H	--	32→39	H	H	--				
	8-27	M	H	--	39→64	M	H	--	0-32	M	H	--
	27-32	H	H	--								
3-4	0-3	M	H	--	32→42	M	H	--	0-21	M	H	--
	3-6	M	H	--	54←32	H	--	--	21-24	M/H	H	--
	6-25	L/M	H	--					24-32	H	H	--
	25-32	M	H	--								
3-5	0-2	L	H	--	32→48	M	H	--	0-24	M	H	--
	2-32	M	M	--	48←32	H	H	--	24-32	H	H	--
3-6	0-2	L	H	--	32→61	M	H	--	0-18	M	H	--
	2-21	L/M	H	--	35←32	M	H	--	18-32	M	H	--
	21-32	M	H	--								
3-7	0-2	O	M	--	32→39	M	M	--	0-4	L/M	M	--
	2-32	M	M	--	57←32	M/H	M	--	4-32	M	M	--
3-8	0-4	L	H	--	32→56	M/H	H	--	0-16	H	H	--
	4-18	M	M	--	40←32	M	M	--	16-32	L/M	M	--
	18-32	M	H	--								
3-9	0-5	L	H	--	32→43	H	L	--	0-25	H	L	--
	5-27	M	M	--	53←32	M	M	--	25-32	M	M	--
	27-32	H	L	--								
3-10	0-5	L	H	--	32→42	H	M	--	0-10	M	H	--
	5-26	M	M	--	54←32	M	H	--	10-32	M	H	--
	26-32	H	M	--								
3-11	0-3	L	M	--	32→39	H	H	--	0-18	M	H	--
	3-23	L/M	M	--	57←32	M	M	--	18-32	M	M	--
	23-32	H	H	--								

(Continued)

Note: L = light; M = moderate; H = heavy; L/M = light to moderate; M/H = moderate to heavy; O = none.
* Strands of beam 3 were cleaned before tarnishing could be recorded.
** ← denotes distance from the landward end; → denotes distance from the seaward end.

(Sheet 1 of 6)

Table 10 (Continued)

Strand	Distance from Landward End, in.	Landward End: Rusting	Landward End: Pitting	Landward End: Tarnishing	Distance from Ends, in.	Midsection: Rusting	Midsection: Pitting	Midsection: Tarnishing	Distance from Seaward End, in.	Seaward End: Rusting	Seaward End: Pitting	Seaward End: Tarnishing
					Beam 3 (Continued)							
3-12	0-3	M	H	--	32→35	H	H	--	0-29	H	H	--
	3-32	H	H	--	35→46	M	H	--	29-32	H	H	--
					50←32	H	H	--				
					Beam 9							
9-1	0-32	L/M	M	M	32→64	L	M	M	0-32	M	M	M
					Beam 13							
13-1	0-8	H	L	L	46→50	H	M	M	0-12	M	L	L
	8-24	M	L	L					12-32	L	L	L
	24-32	L	O	O								
13-2	0-4	M	O	M	32→64	M	M	M	0-4	L	M	M
	4-22	M	L	L					4-12	M	M	M
	22-32	L	L	L					12-18	L	M	M
									18-32	M	M	M
13-3	0-12	H	H	H	32→64	M	L	L	0-18	M	L	L
	12-14	M	L	L					18-32	L	O	O
	14-22	L	L	L								
13-4	0-8	H	H	H	32→64	M	L	L	0-18	M	L	L
	8-20	M	L	L					18-32	L	L	L
	20-32	L	L	L								
13-5	0-4	H	H	H	32→40	L	O	O	0-32	M	L	L
	4-9	H	M	M	40→52	M	L	L				
	9-32	M	O/L	O/L	38←32	L	O	O				
					44←38	M	L	L				
13-6	0-8	H	L	L	42→48	M	L	L	0-18	M	L	L
	8-24	M	L	L	44←36	L	O	O	18-32	L	O	O
13-7	0-3	H	H	H	32→64	M	M	M	0-12	L	M	M
	3-24	M	M	M					12-32	M	M	M
	24-32	L	M	M								
13-8	0-10	H	H	H	32→64	L	M	M	0-32	L	M	M
	10-24	M	M	M								
	24-32	L	M	M								

(Continued)

Table 10 (Continued)

Strand	Distance from Landward End, in.	Landward End Rusting	Landward End Pitting	Landward End Tarnishing	Distance from Ends, in.	Midsection Rusting	Midsection Pitting	Midsection Tarnishing	Distance from Seaward End, in.	Seaward End Rusting	Seaward End Pitting	Seaward End Tarnishing
						Beam 15						
15-1	0-6	M	M	H	32→64	L	L	M	0-32	L	L	M
	6-14	H	H	M								
	14-32	L	L	M								
15-2	0-18	M	M	M	32→64	L	L	M	0-10	M	L	L
	18-32	L	L	M					10-32	L	L	L
15-3	0-16	M	L	M	32→64	L	L	M	0-32	L	L	M
	16-32	L	M	M								
15-4	0-8	L	L	M	32→64	L	L	M	0-32	L	L	L
	8-12	M	M	M								
	12-32	L	L	M								
15-5	0-6	M	M	H	32→64	L	L	M	0-32	L	L	M
	6-14	H	H	M								
	14-32	L	L	M								
15-6	0-12	M	H	H	32→64	L	L	M	0-32	L	L	M
	12-32	L	M	M								
15-7	0-14	M	M	H	32→64	L	L	M	0-32	L	L	M
	14-32	L	L	M								
15-8	0-5	L	H	H	32→64	L	L	L	0-32	L	L	M
	5-14	M	M	H								
	14-32	L	L	M								
						Beam 19						
19-1	0-10	L	M	M	32→64	L	M	M	0-24	L	M	M
	10-24	M	L	M					24-32	L	M	M
	24-32	H	M	M								
19-2	0-10	L	M	L	32→64	L	L	M	0-32	L	M	M
	10-32	M	M	H								
19-3	0-8	L	M	M	32→64	L	L	M	0-32	L	M	M
	8-32	M	M	M								
19-4	0-8	L	L	M	32→64	L	L	M	0-24	L	L	M
	8-12	M	M	M					24-32	L	L	M
	12-32	L	L	M								
19-5	0-32	L	L	M	32→64	L	L	M	0-32	L	L	M

(Continued)

(Sheet 3 of 6)

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Table 10 (Continued)

Strand	Distance from Landward End, in.	Landward End Rusting	Landward End Pitting	Landward End Tarnishing	Distance from Ends, in.	Midsection Rusting	Midsection Pitting	Midsection Tarnishing	Distance from Seaward End, in.	Seaward End Rusting	Seaward End Pitting	Seaward End Tarnishing
					Beam 19 (Continued)							
19-6	0-24	L	L	M	32→64	M	L	M	0-8	L	M	M
	24-32	L	M	L					8-24	L	L	M
									24-32	M	L	M
19-7	0-13	L	M	L	32→64	M	L	L	0-32	L	M	M
	13-32	M	L	L								
19-8	0-32	L	L	M	32→64	L	L	M	0-32	L	L	M
19-9	0-15	L	L	L	32→64	L	L	M	0-8	M	L	M
	15-32	L	M	M					8-32	L	L	M
19-10	0-8	L	L	M	32→64	M	L	M	0-24	M	L	M
	8-18	L	L	M					24-32	L	L	M
	18-32	M	L	M								
19-11	0-18	L	L	M	32→60	L	L	L	0-18	M	L	M
	18-32	L	M	M	36←32	H	L	L	18-32	M	L	M
19-12	0-32	L	L	M	32→64	L	L	M	0-8	M	L	M
									8-32	L	L	M
					Beam 1							
1-1	0-32	M	H	H	32→48	L	H	H	0-12	L	M	M
					32←48	M	H	H	12-32	M	M	M
1-2	0-32	M	H	H	32→40	M	H	H	0-32	L	M	H
					40→49	H	H	H				
					32←47	M	H	H				
1-3	0-9	M	H	H	32→64	M	H	H	0-12	L	H	H
	9-25	H	H	H					12-32	M	H	H
	25-32	M	H	H								
1-4	0-32	M	H	H	32→64	M	M	H	0-9	L	H	H
									9-32	M	H	H
1-5	0-32	M	H	H	32→64	M	H	M	0-32	M	H	H
	0-32	M	H	H	32→40	M	H	H	0-12	M	M	H
					40→53	M	M	M	12-20	M	L	M
					32←43	M	M	H	20-32	M	H	H
1-7	0-14	L	H	H	32→45	M	M	H	0-32	L	M	M
	14-32	M	H	H	32←51	M	M	M				

(Continued)

Table 10 (Continued)

Strand	Distance from Landward End, in.	Landward End			Distance from Ends, in.	Midsection			Distance from Seaward End, in.	Seaward End		
		Rusting	Pitting	Tarnishing		Rusting	Pitting	Tarnishing		Rusting	Pitting	Tarnishing
						Beam 1 (Continued)						
1-8	0-32	M	M	H	32→64	M	M	H	0-14	L	M	M
									14-32	M	M	M
1-9	0-32	M	M	H	32→42	M	H	M	0-32	L	H	H
					32←54	M	M	M				
1-10	0-32	M	M	M	32→40	M	M	H	0-32	M	H	H
					40→48	M	M	M				
					32←48	L	H	M				
1-11	0-14	H	H	H	32→40	M	L	M	0-32	M	M	M
	14-22	M	M	H	32←56	M	M	M				
	22-32	M	L	M								
1-12	0-14	M	M	H	32→48	M	M	H	0-11	M	M	M
	14-32	H	M	H	32←48	M	M	M	11-32	M	H	H
						Beam 6						
6-1	0-10	M	M	M	32→64	M	H	H	0-32	M	H	H
	10-32	M	H	H								
6-2	0-32	M	M	H	32→64	M	M	H	0-13	L	M	M
									13-32	M	H	H
6-3	0-10	H	H	M	32→58	M	H	H	0-13	L	M	H
	10-32	M	M	H	58→64	H	H	H	13-32	M	H	H
6-4	0-32	M	M	H	32→64	M	M	H	0-13	L	M	H
									13-25	M	M	H
									25-32	H	M	M
6-5	0-32	M	M	H	32→64	M	M	M	0-10	L	L	H
									10-26	M	M	M
									26-32	H	M	M
6-6	0-32	M	L	M	32→64	M	M	M	0-13	L	L	H
									13-32	M	M	M
6-7	0-10	M	H	H	32→64	M	L	M	0-32	M	M	H
	10-32	M	L	M								
6-8	0-32	M	M	M	32→64	M	M	M	0-13	L	L	H
									13-32	M	L	M
6-9	0-10	M	M	H	32→64	M	L	M	0-10	L	L	M
	10-32	M	M	M					10-32	M	L	M

(Continued)

(Sheet 5 of 6)

Table 10 (Concluded)

Strand	Distance from Landward End, in.	Landward End			Distance from Ends, in.	Midsection			Distance from Seaward End, in.	Seaward End		
		Rusting	Pitting	Tarnishing		Rusting	Pitting	Tarnishing		Rusting	Pitting	Tarnishing
						Beam 6 (Continued)						
6-10	0-32	M	M	M	32→45	M	M	M	0-13	L	L	H
					45→64	M	L	M	13-24	M	M	H
									24-32	H	M	H
6-11	0-32	M	L	M	32→64	M	L	H	0-13	L	M	H
									13-32	M	M	H
6-12	0-20	M	M	M	32→64	M	L	M	0-15	L	L	H
	20-32	M	L	M					15-32	M	M	H
						Beam 11						
11-1	0-22	M	H	H	32→64	M	M	M	0-18	M	M	H
	22-32	M	M	M					18-32	M	M	M

Table 11

Constituents of Iron Oxide Samples

Strand No.	Alpha Iron	Magnetite	Goethite	Grout	$CaCO_3$	Quartz	Hematite
Beam 3							
3-1	X	X	X	X			
3-2	X	X	X	X			
3-3			X	X			
3-4		X	X	X			
3-5			X	X			
3-6		X	X	X			
3-7	X	X	X				
3-8	X	X	X				
3-9		X	X	X			
3-10		X	X	X			
3-11	X	X	X	X			
3-12			X	X			
Beam 9							
9-1	X	X		X			
Beam 13							
13-1		X	X		X*		
13-2		X	X				
13-3		X	X				
13-4		X	X				
13-5	X	X	X				
13-6		X	X				
13-7		X	X				
13-8		X	X				

(Continued)

Note: X indicates presence.
* Identified on the basis of one peak.

Table 11 (Concluded)

Strand No.	Alpha Iron	Magnetite	Goethite	Grout	$CaCO_3$	Quartz	Hematite
			Beam 15				
15-1	X	X	X	X	X		
15-2	X	X	X	X	X		
15-3	X	X	X	X	X		
15-4	X	X	X	X	X	X	
15-5	X	X	X	X	X		
15-6	X	X	X	X	X	X	
15-7	X	X	X	X	X		X*
15-8	X	X	X	X	X		
			Beam 19				
19-1	X	X	X	X	X		
19-2	X	X	X	X	X		
19-3	X	X	X	X	X		
19-4	X	X	X	X	X		
19-5	X	X	X	X	X		
19-6	X	X	X	X	X	X	
19-7	X	X	X	X	X		
19-8	X	X	X	X	X	X	
19-9	X	X	X	X	X		
19-10	X	X	X	X	X		
19-11	X	X	X	X	X		
19-12	X	X	X	X	X		

* Identified on the basis of one peak.

Photo 1. Corrosion to strands of the landward end anchorage of beam 3

Photo 2. Condition of steel of the seaward end anchorage beam 3

Photo 3. Heavy rusting to outside of the landward end anchorage plate in beam 9

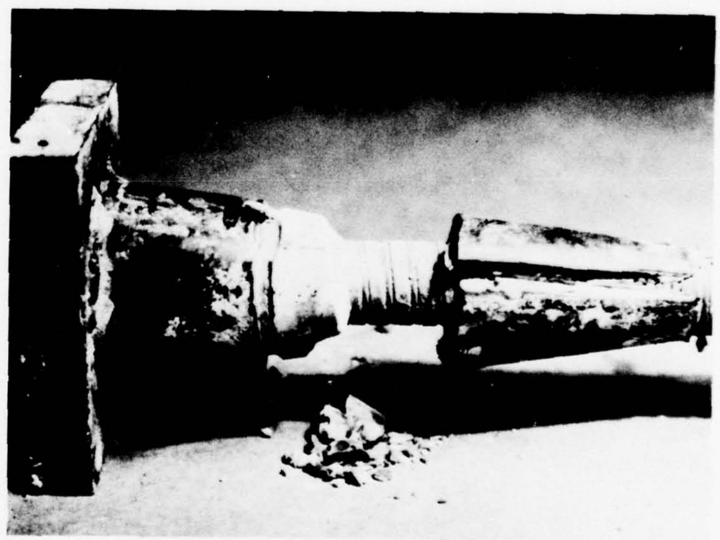


Photo 4. Grout in the landward end housing of beam 9 leaving cavity between housing and conduit

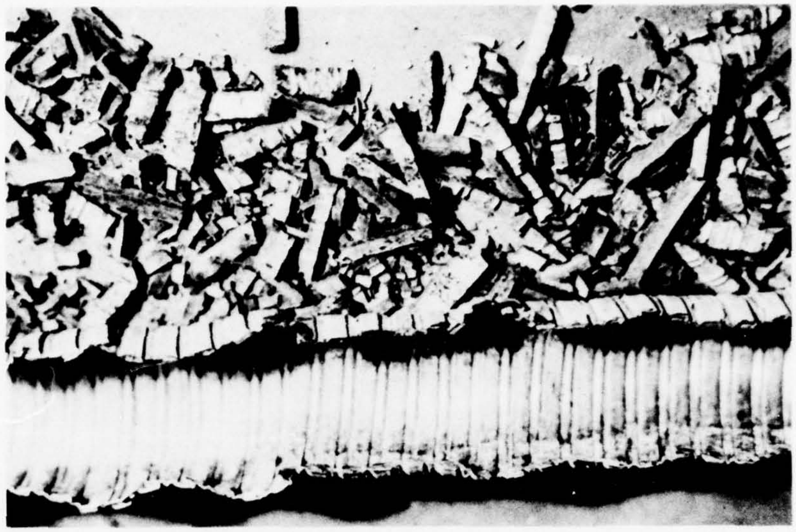


Photo 5. Grout from the landward end of conduit in beam 9

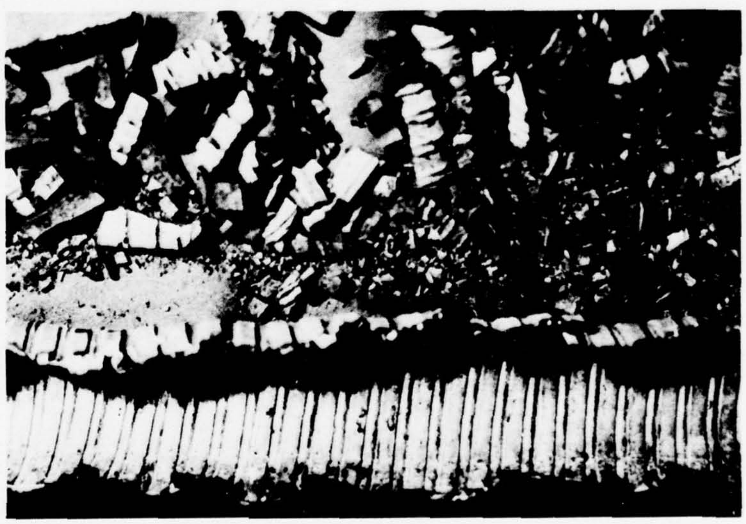


Photo 6. Grout pieces from bottom of conduit in beam 9 thicker and more elongated than those from top of conduit due to thicker grout cover on bottom

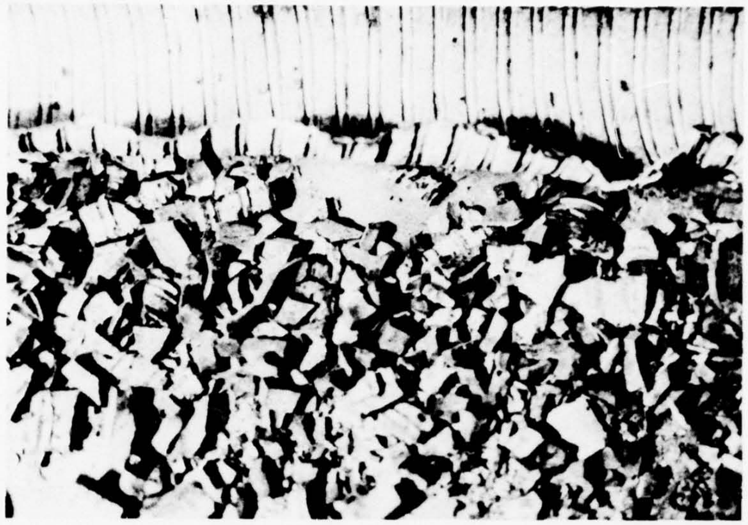


Photo 7. Central section of bottom of conduit in beam 9 and its pieces of grout

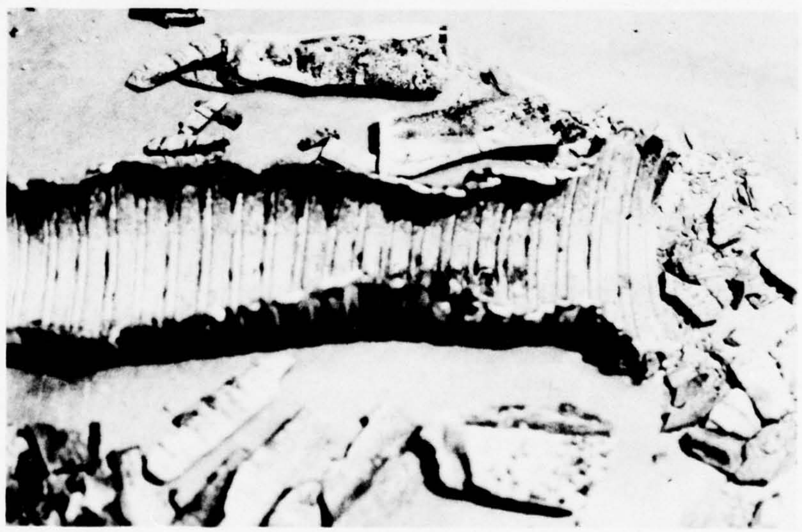


Photo 8. Seaward end of conduit in beam 9 at the funnel housing and an isolated patch of heavy rust

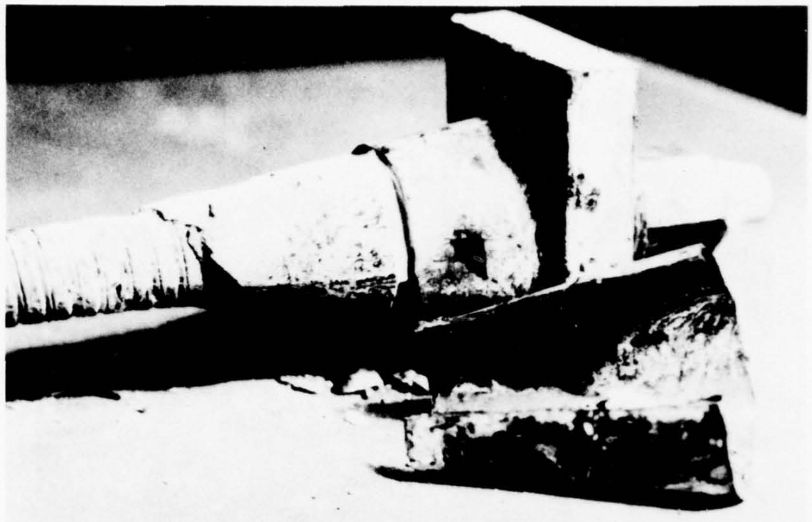


Photo 9. Condition of the seaward end anchor of beam 9

Photo 10. Grout around the ends of strands in beam 13 discolored by rust

Photo 11. Edges of the landward end anchor of beam 13 lightly to moderately rusted. Note heavy rust to strands and broken strand just inside end plate

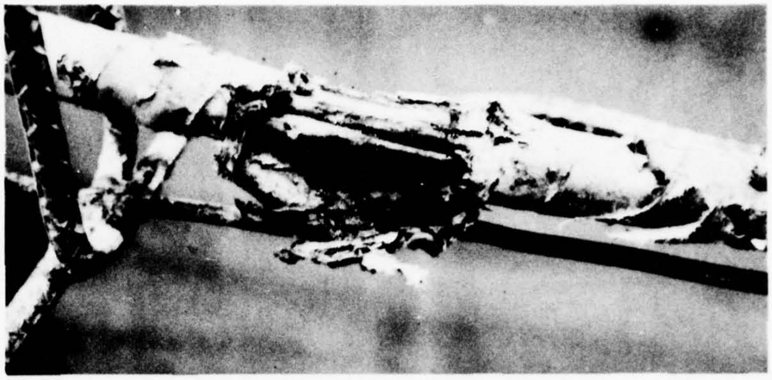


Photo 12. Paper-type wrapping in beam 13 torn, exposing grease and strands

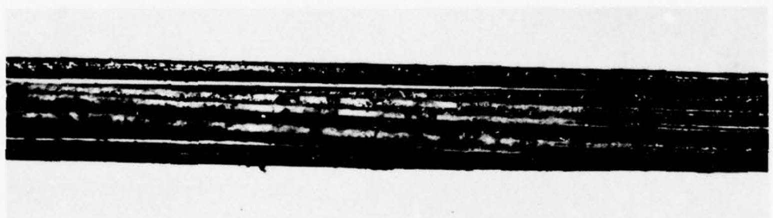


Photo 13. General view of strands in beam 13 showing rusted areas, and moist and dry grease

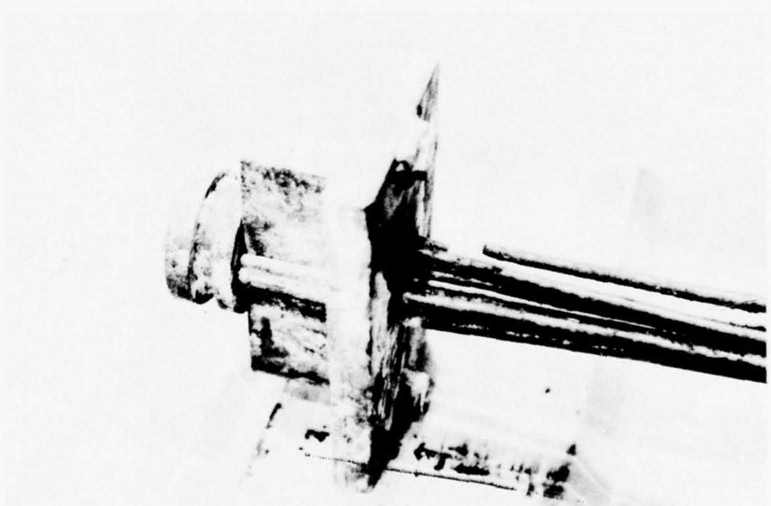


Photo 14. Strand in beam 13 so badly rusted that it broke about 5/8 in. from inside face of the end anchorage

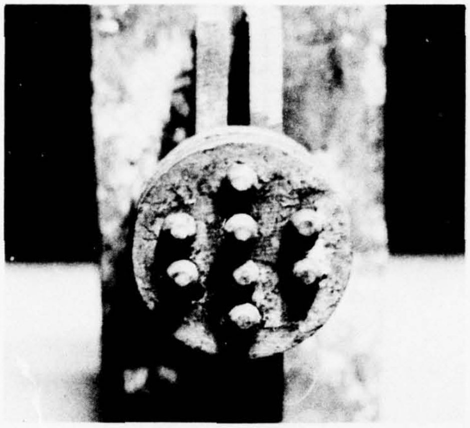


Photo 15. Heavy rusting to round anchor plate on outside face of the seaward end of beam 13

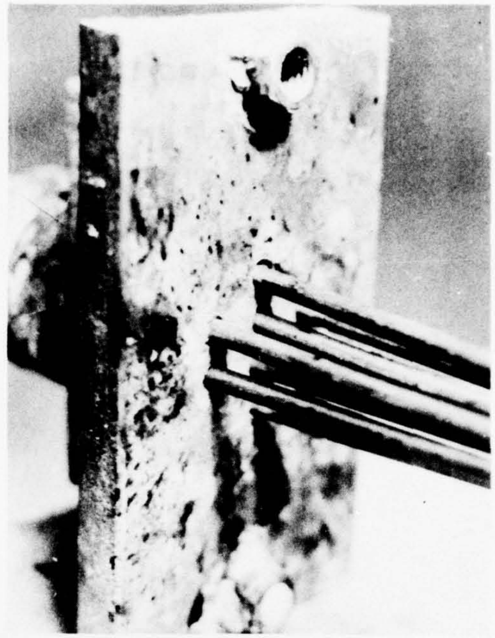


Photo 16. Inside face of the seaward anchorage of beam 13 exhibiting tarnishing and pitting

Photo 17. Heavy rusting on the inside face of the seaward anchorage of beam 13 where strands passed through the plate

Photo 18. Outside of the landward end anchorage of beam 15 showing extent of rust and concrete cover

Photo 19. Detail of Photo 18 showing how surface of steel was rusted under the concrete cover

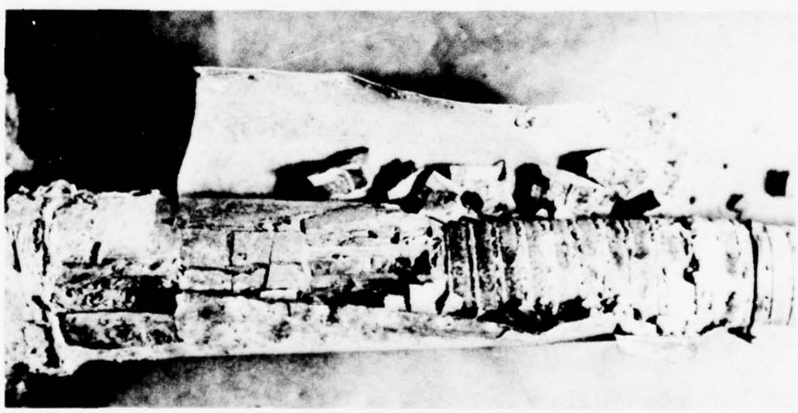


Photo 20. In beam 15, portion of conduit at the landward end that was heavily rusted with tiny pitting rust spots

Photo 21. Strands beneath the landward end housing in beam 15 with moderate rust cover

Photo 22. Weak grout and lustrous conduit beneath the seaward end housing in beam 15

Photo 23. Grout at the seaward end in beam 15 just after conduit was opened. Note longitudinal crack, relieving the remaining stress in the steel

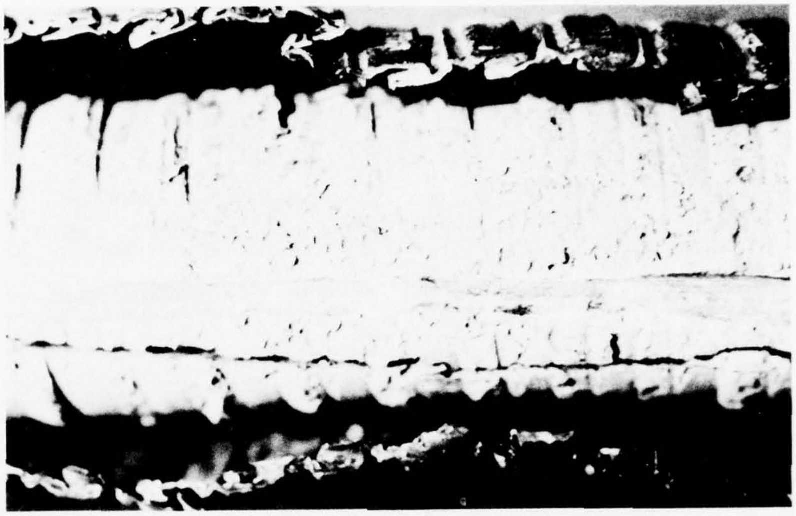


Photo 24. Detail of Photo 23 showing laitance and air voids in the grout

Photo 25. Condition of the strands beneath the grout in beam 15 showing light rust cover

Photo 26. Grout at top of conduit near the landward end of beam 15. Note thin grout due to closeness of strands to top of conduit

Photo 27. Off-center orientation of strands of beam 15

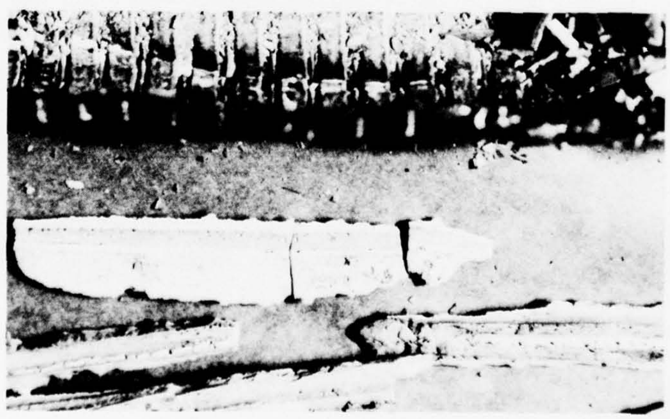


Photo 28. Grout from conduit at the seaward end of beam 15. Note milky white powder (calcium carbonate) covering grout and area of conduit from which the grout was taken

Photo 29. Heavy corrosion to the landward end anchorage of beam 19. Note rusted and flaked metal

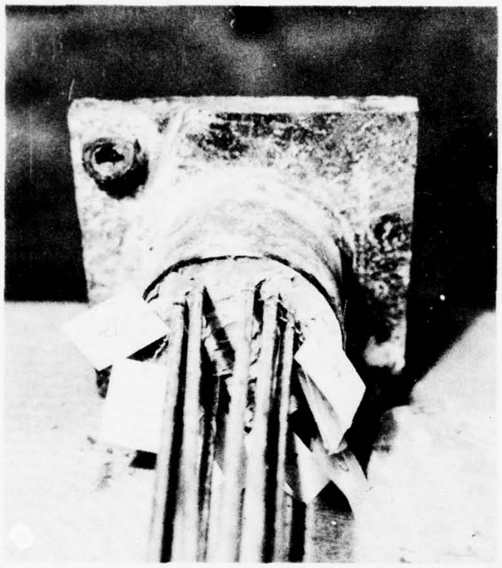


Photo 30. Heavy scarring and tarnishing on inside of the landward end anchorage plate of beam 19. Note light rusting with patches of heavy rusting

Photo 31. Grout beneath the seaward end funnel housing of beam 19 with less than 30 percent coverage of rust

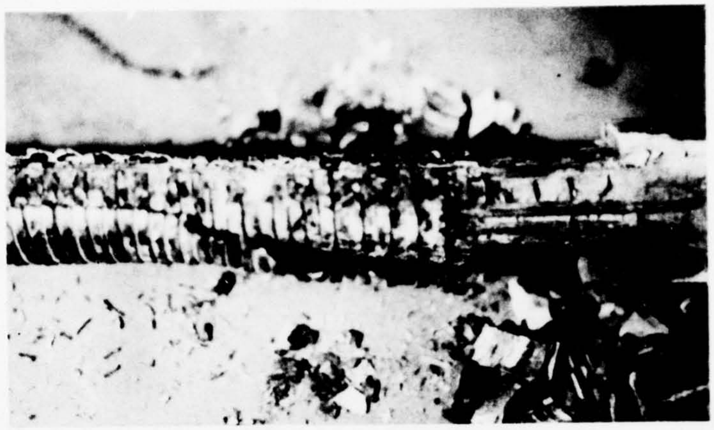


Photo 32. Heavily rust-stained grout beneath conduit at the seaward end of beam 19

Photo 33. Air voids found at the grout-conduit interface of central section of beam 19

Photo 34. Rust stains on grout inside the landward end funnel in beam 19

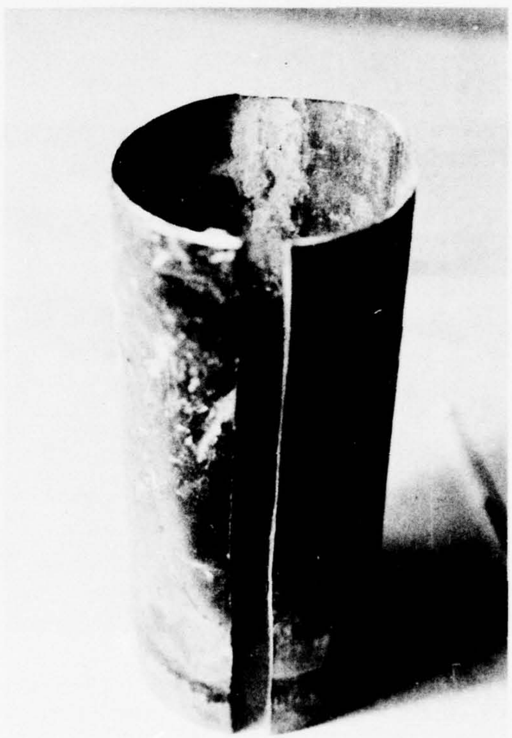


Photo 35. Rust on inside of the landward end funnel housing of beam 19

Photo 36. Strands at the landward end housing in beam 19. Note light to moderate rust with light pitting and small spots of heavy rust

Photo 37. Heavy rust on outside face of the seaward anchorage and strands in beam 19

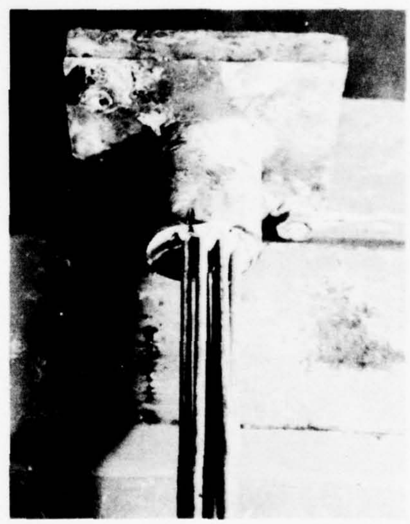


Photo 38. Inside face of the seaward end anchorage plate in beam 19. Note heavy tarnishing and moderate pitting but no rust

Photo 39. Detail of beam used in the second investigation showing moisture on the surface of the concrete

Photo 40. Pools of water around the conventional reinforcement of beams used in the second investigation

Photo 41. Rusting at the conduit/end anchorage joint in beam 6

Photo 42. Epoxy cover on the strands at the outside end of beam 1

Photo 43. Heavy rusting to the ends of the strands at the outside end of beam 1. Note epoxy cover on the strands

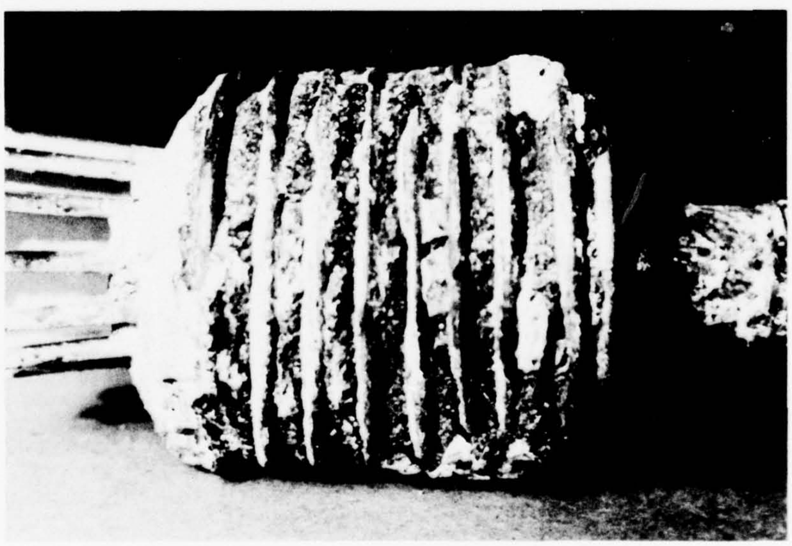


Photo 44. Landward end anchorage of beam 6. Note cement bonded to steel coils and tarnishing on coils but no rusting

Photo 45. Strands extending 1-1/4 in. from the landward end anchorage of beam 6 completely free of rust

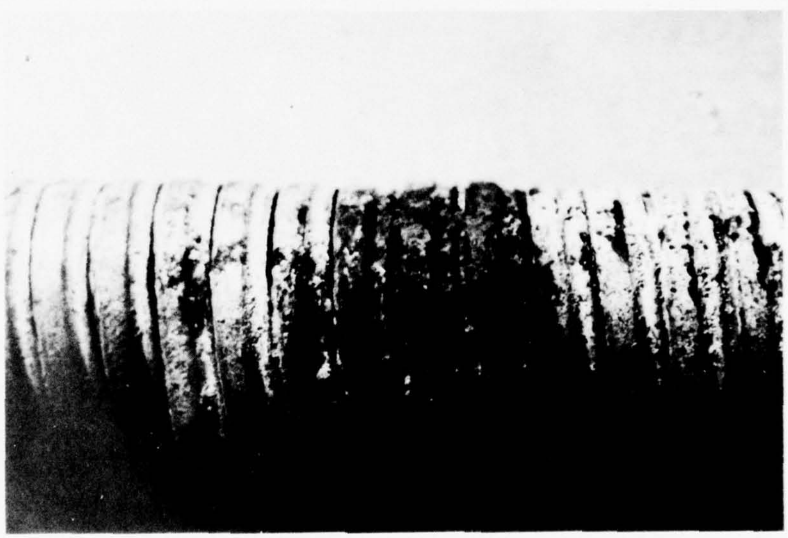


Photo 46. Heavily corroded area on midsection of conduit in beam 6

Photo 47. Midsection of conduit in beam 6 showing heavily corroded areas with holes when conduit had completely deteriorated

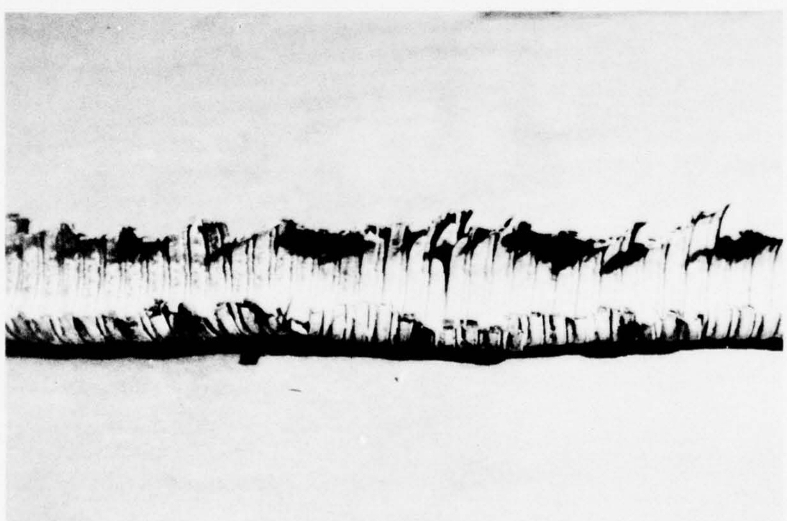


Photo 48. Inside of conduit at the end of beam 6. Note metallic luster still present on inside

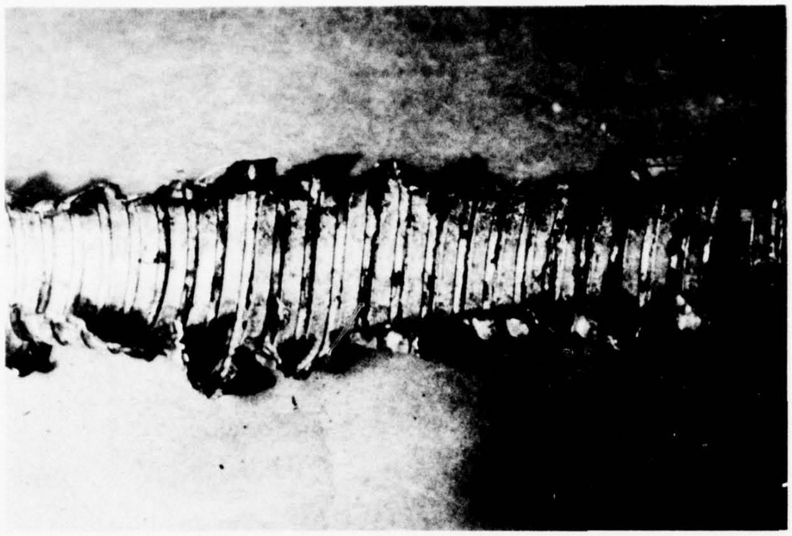


Photo 49. Inside of midsection of conduit in beam 6. Note rust on joints heavier and unrusted surface less lustrous than at ends (Photo 48)

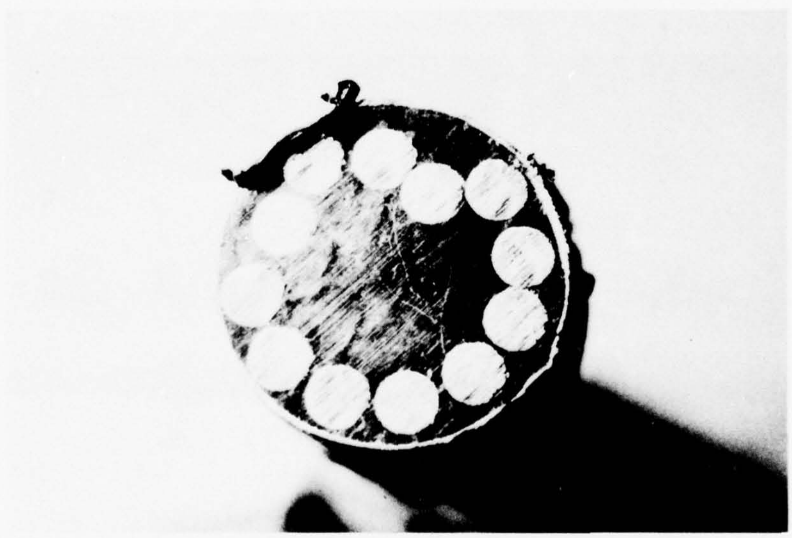


Photo 50. Landward end of conduit in beam 6 immediately after it was cut from conduit. Note closeness of individual strands to outside of conduit and contact of some strands with other strands and inside of the conduit

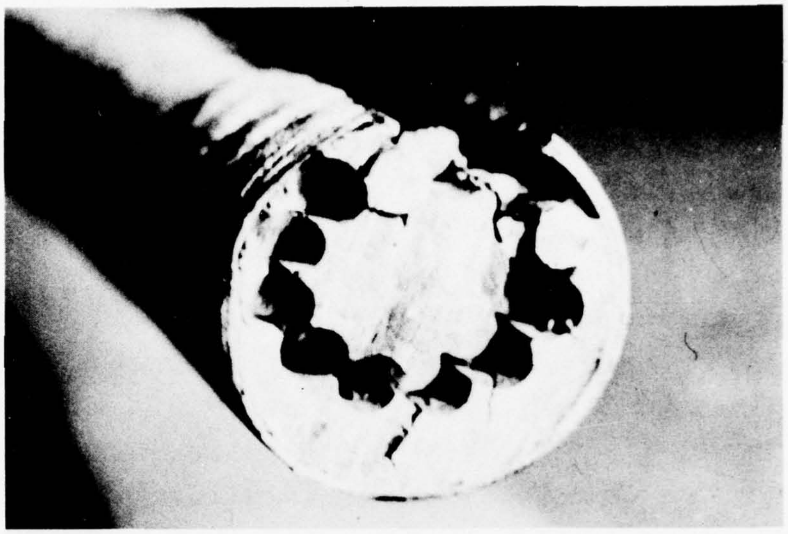


Photo 51. Strands at the seaward end of conduit in beam 6 after conduit was cut lengthwise. Note that 3 of the 12 strands did not shorten when the grout-steel bond failed

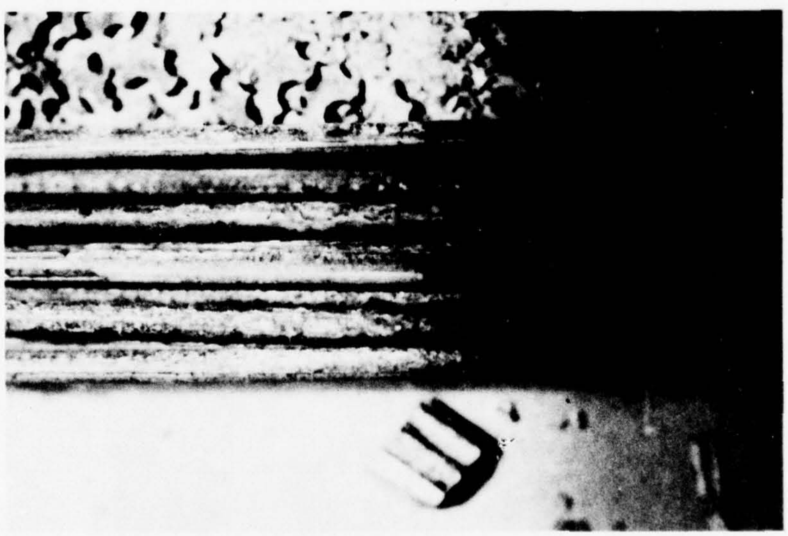


Photo 52. Strands in beam 6 with spots of heavy rust caused by contact with inside of conduit

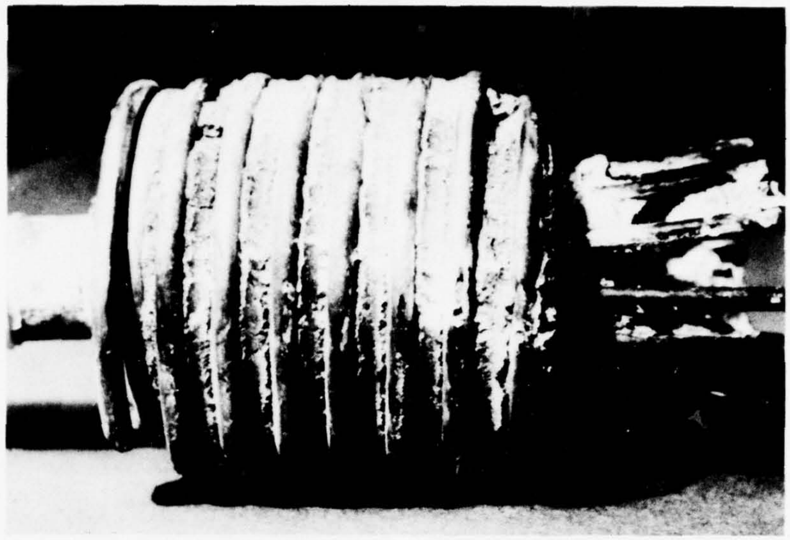


Photo 53. Steel coils of the seaward end anchorage of beam 6 lightly rusted at some spots and lustrous and unpitted in other areas

Photo 54. Poor compaction of the epoxy concrete end anchorage protection at the landward end of beam 11

Photo 55. Poor compaction of the epoxy concrete end anchorage protection at the landward end of beam 11 showing rust on edge of anchor plate

Photo 56. Rust to outside of the landward end anchorage plate of beam 11

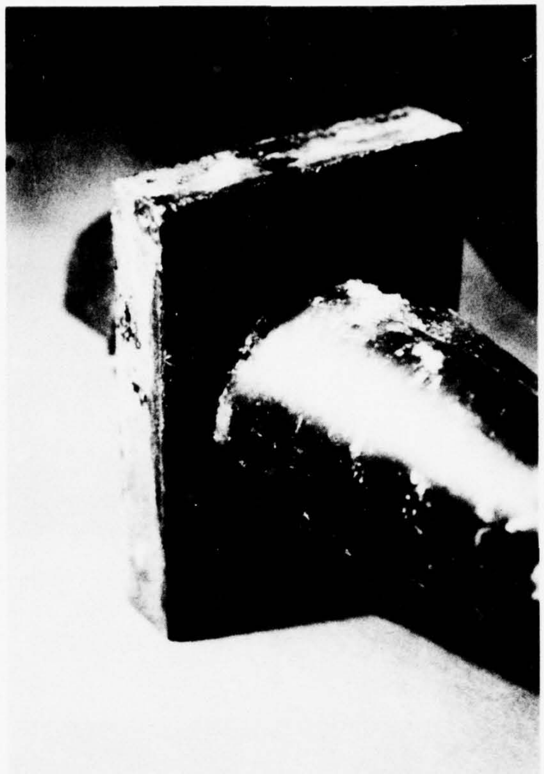


Photo 57. Inside face of the landward end anchorage plate of beam 11 not rusted but heavily tarnished

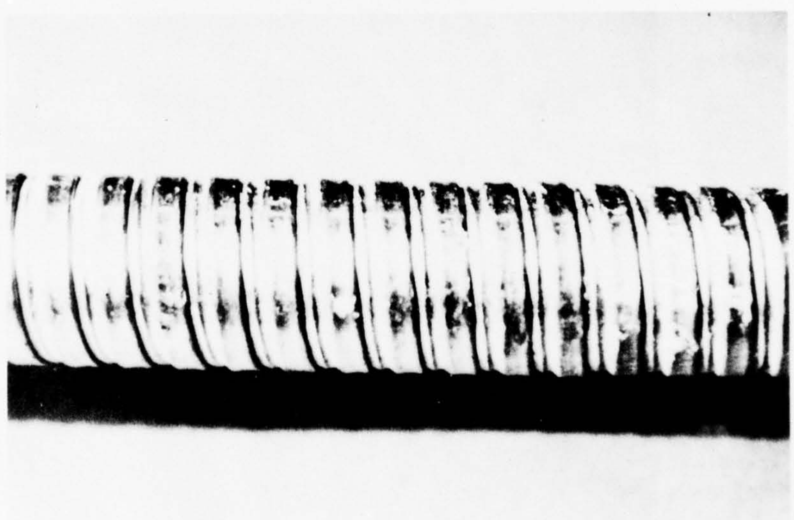


Photo 58. Highly lustrous condition of the conduit of beam 11, showing no rust and lack of any cement bonded to the surface of the metal

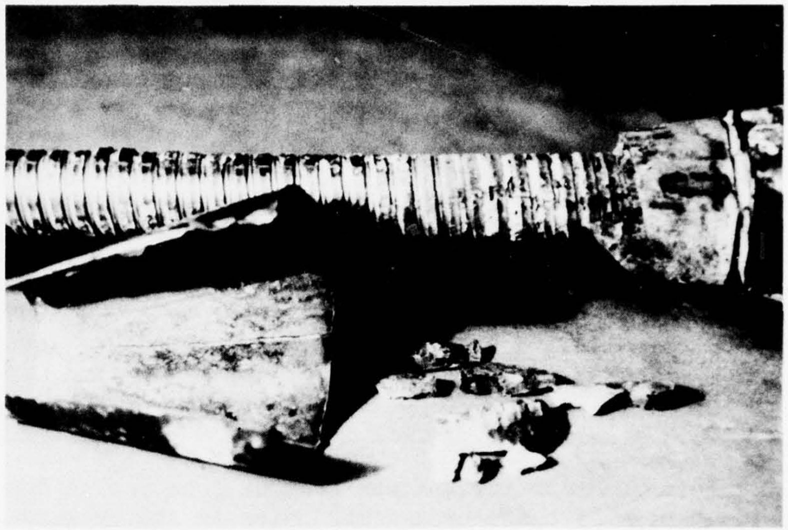


Photo 59. Rust on the bottoms of the funnel housing and conduit of beam 11 and pieces of grout that penetrated into the funnel housing

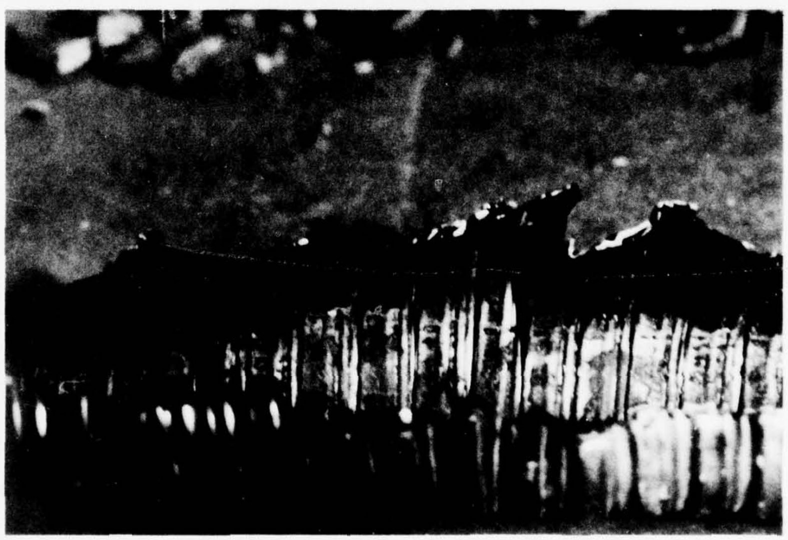


Photo 60. Bottom half of conduit in beam 11. Note border areas on both sides of 1-in.-wide strip of rust

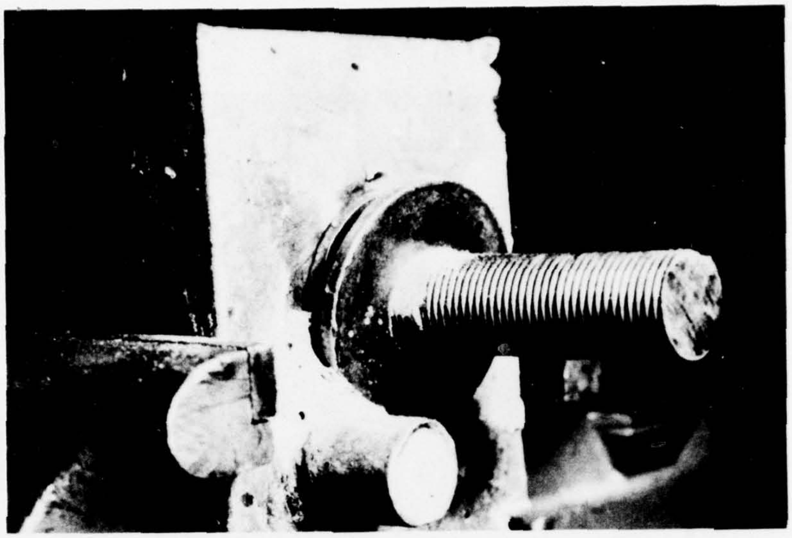


Photo 61. Rust on threads where grout from inside conduit in beam 11 came through the holes in the seaward end anchorage plate and washers. Note outside face of plate lightly rusted at top and free of rust at bottom

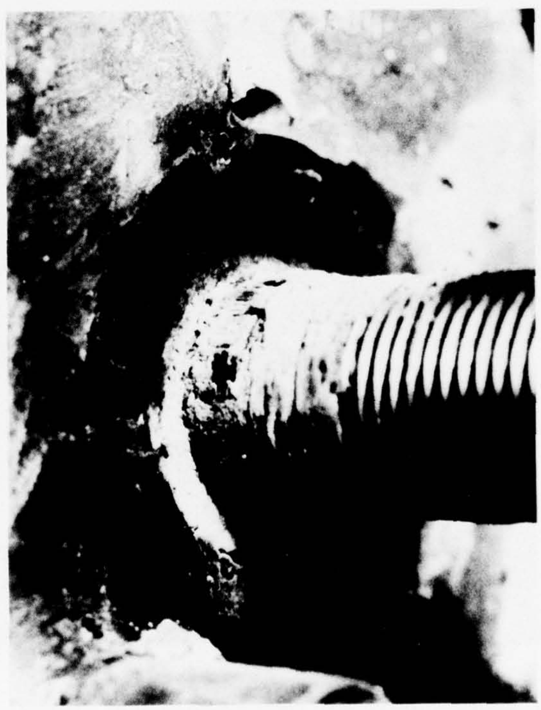


Photo 62. Detail of the seaward end anchorage plate in beam 11 not very rusted except at hole

APPENDIX A: RESULTS OF STRUCTURAL TESTING OF POSTTENSIONED BEAMS

Beam 3

1. Beam 3 had no spalled areas at the supports and therefore required no patching for structural testing. The loading rate for the beam was 2,000 lb/min. First cracking was observed at a load of 41,357 lb, and the midspan deflection was 0.145 in. Photo A1 shows the series of crack patterns from zero load to ultimate load. The beam failed at an ultimate load of 78,928 lb in flexural shear at the landward end. The final midspan deflection was 0.600 in. Even though there was ample warning that the beam was failing, the actual failure occurred instantaneously (Photo A2). When the pieces of broken concrete were removed from the failure area, it was found that the tendon had not failed and that the bond between conduit and concrete was strong. The conventional reinforcement in this area was bent due to the failure, and some of the welds that held the reinforcement cage together were broken. The load-deflection curve for beam 3 is presented in Plate A1.

Beam 9

2. The supports for beam 9 did not need to be repaired, and the beam was loaded at the rate of 2000 lb/min. Photo A3 shows the crack pattern from zero load to failure. Initial cracking was observed at a load of 47,780 lb and a midspan deflection of 0.126 in. Loading was continued, and in the next 20,000 lb of load, six flexure cracks formed. At 70,000 lb, flexure-shear cracks began to propagate. At approximately 78,000 lb, the load began to drop off and at 80,976 lb ultimately failed. The midspan deflection was 0.458 in. The beam failed in shear at the seaward end as shown in Photo A4. The failure of this beam was also instantaneous although it was apparent that it would fail in shear where it did. The conventional reinforcement was bent, and some of the welds holding the cage together were broken at failure. The tendon did not fail by breaking since it consisted of one 7/8-in.-diam bar, but at the seaward end where the beam failed, the posttensioned bar was bent enough to constitute a failure. It should be noted that the strands in the

other beams did not bend at the point of concrete failure because each strand had a high slenderness ratio compared to that of the bar in beam 9 and was therefore much more flexible. The load-deflection curve for beam 9 is presented in Plate A2.

Beam 13

3. Photo A5 shows the crack propagation of beam 13 from zero to ultimate load, as well as some postfailure load and displacements. Photo A5b shows the crack propagation at 45,000 lb. The actual crack initiation in this beam occurred between 40,000 and 45,000 lb. The midspan deflection at crack initiation was 0.110 in. The beam failed at an ultimate load of 61,713 lb and a midspan deflection of 0.600 in. Loading was continued after failure to see what deflections were possible and the amount of tendon rebound. At a deflection of 0.800 in. under a load of 51,600 lb, the beam made a loud popping noise that was assumed to be conventional reinforcement breaking. The beam was loaded to produce total deflections of 1.00, 1.50, 2.00, and 2.30 in. These deflections occurred under loads of decreasing magnitude of 42,040, 37,942, 37,250, and 37,250 lb, respectively. After final removal of load, the beam rebounded approximately 2 in. The beam failed in pure flexure at the landward end third point of the beam (Photo A6). When the testing was completed, it was determined that one of the eight strands had been broken by the structural testing. The conduit of this beam was made of paper; therefore, there was no bond strength developed between the concrete and conduit. The load-deflection curve for beam 13 is presented in Plate A2.

Beam 15

4. Beam 15 was loaded at the constant rate of 2000 lb/min after it was found that no repair work to the support points was needed. The first cracks appeared at a load of 40,000 lb and a midspan deflection of 0.083 in. After the initial cracking, the beam made popping sounds at

loads of 50,000, 55,000, and 65,000 lb. Failure began to become apparent at 70,000 lb when a crack widened and the pressure from the loading apparatus dropped. The deflection here was 0.370 in. At 73,462 lb, the concrete began to spall from the conventional reinforcement, and at 74,828 lb, the beam failed in shear at the landward end (Photos A7 and A8). At ultimate load, the tendon was in good condition, and the concrete was well bonded to the conduit. The final midspan deflection was 0.590 in. The load-deflection curve for beam 15 is presented Plate A3.

Beam 19

5. Photo A9 shows the sequence of crack propagation for beam 19. The first crack was observed at a load of 45,000 lb and a midspan deflection of 0.077 in. Loading continued at 2000 lb/min, and popping sounds were heard at 55,000, 65,000, and 70,000 lb. At 80,000 lb and a deflection of 0.275 in., shear cracks began to form. The last midspan deflection reading that was made was 0.386 in. at 93,000 lb. The beam failed in shear at a load of 93,954 lb; no deflection reading was made. The shear failure occurred at the landward end of the beam as shown in Photo A10. It is especially important to note that the shear failure occurred directly between the vertical shear reinforcements. As shown in Photo A10, the shear reinforcement for each beam was placed on centers three-fourths the depth of the beam, or 12-in. centers. When the concrete was removed, it was found that there was good bond between the concrete and the conduit and that the strands did not exhibit any failure. The load-deflection curve for beam 19 is presented in Plate A3.

Beam 1

6. Beam 1 was not tested structurally so that its posttensioning strands could be tested without previously being subjected to the stress caused by structural testing.

Beam 6

7. After the loading and supporting areas were marked, beam 6 was found to need repair to its landward support area. An epoxy patch was placed over the spalled area and allowed to harden for 24 hr prior to testing. The loading rate, as in the first investigation, was 2000 lb/min. It was first observed that cracks were developing at a load of 36,600 lb and a midspan deflection of 0.092 in. Observations were made at each 5,000-lb increment, and crack propagation pictures (Photo A11) were made at 50,000, 65,000, 70,000, and at failure condition of 75,000 lb and midspan deflection of 0.379 in. This type of failure (Photo A12) was described as a flexural shear failure with spalling of the concrete at the top and bottom supports. The conventional reinforcement was bent and had welds broken, but the conduit inside was unbroken and not bent. The bond between concrete and conduit was good. The load-deflection curve for beam 6 is presented in Plate A4.

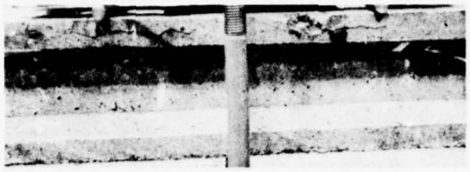
Beam 11

8. The supports of beam 11 did not need repair. Photo A13 shows the crack pattern from zero load to failure. The beam first cracked at a load of 48,870 lb and a midspan deflection of 0.110 in. Loading continued as shown in the photograph until failure at 87,800 lb and 0.563-in. deflection. The mode of failure was flexural cracking with the conventional reinforcement cage causing spalling at the top and bottom edges.

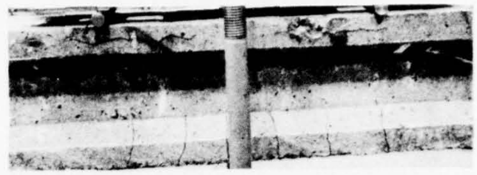
9. In the failure condition, as shown in Photo A14, the conventional reinforcement was broken in spots, but the conduit inside the beam did not bend. There was instantaneous failure when the beam broke, but unlike the testing of beam 9 in which the bar actually bent, this bar did not. The load-deflection curve for beam 11 is presented in Plate A4.

10. Plates A5-A7 show stress-strain curves for selected strands from beams 1, 3, and 13. Plate A5 shows the characteristics of strand

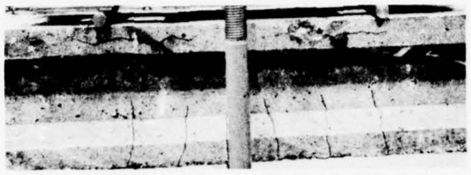
2 of beam 1. This strand was tested without having been previously stressed due to failure of the beam; it was chosen to represent a strand that exceeded all the requirements of ASTM tests. Plate A6 shows the stress-strain curve for strand 6 of beam 3. This strand failed to reach the minimum ultimate stress requirement. Plate A7 shows the characteristics of strand 4 of beam 13. It is included as an example of stress-strain curve for strands that did not pass ultimate stress or total elongation requirements. Plate A8 shows plots of total chloride content (percent by weight of concrete) versus depth from surface of the beam. The chloride contents of the 5-in. cross sections (0.11-0.19 percent) were generally higher than those of the 10-in. sections (0.05-0.15 percent).



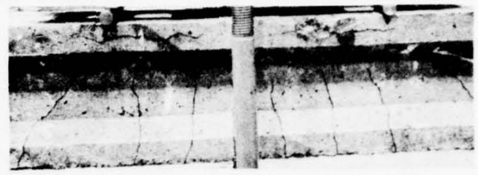
a. No load, 0.00-in. deflection



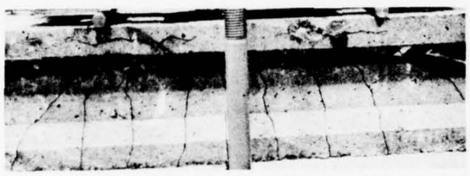
b. First crack, 41,357-lb load, 0.145-in. deflection



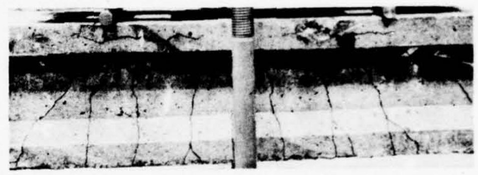
c. 50,000-lb load, 0.185-in. deflection



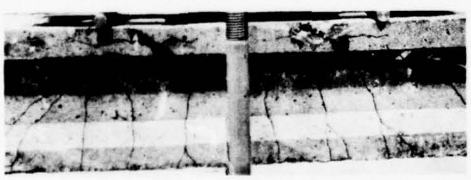
d. 55,000-lb load, 0.223-in. deflection



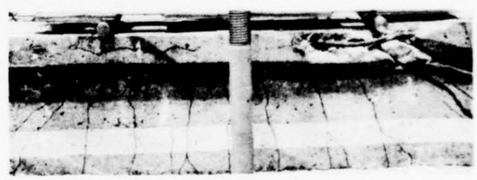
e. 65,000-lb load, 0.320-in. deflection



f. 70,000-lb load, 0.376-in. deflection



g. 75,000-lb load, 0.463-in. deflection

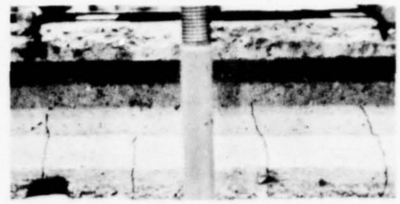


h. Failure, 78,928-lb load, 0.600-in. deflection

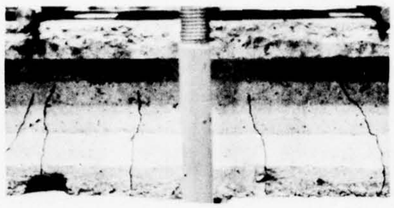
Photo A1. Crack propagation of beam 3

Photo A2. Failure condition of beam 3

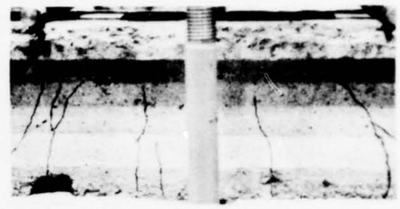
a. No load, 0.00-in. deflection



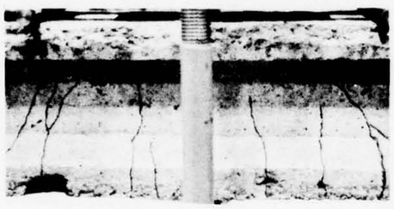
b. First crack, 47,780-lb load, 0.126-in. deflection



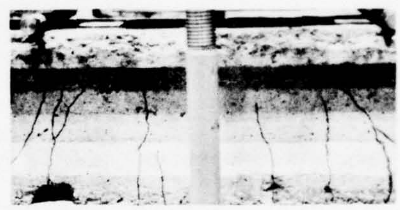
c. 65,000-lb load, 0.161-in. deflection



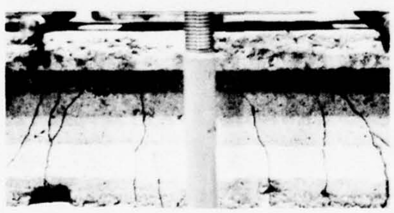
d. 73,462-lb load, 0.318-in. deflection



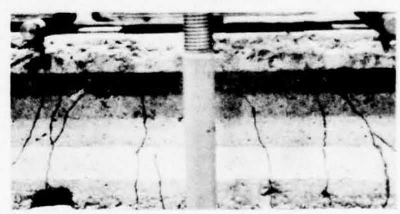
e. 76,194-lb load, 0.354-in. deflection



f. 77,560-lb load, 0.397-in. deflection



g. 80,000-lb load, 0.428-in. deflection



h. Failure, 80,976-lb load, 0.458-in. deflection

Photo A3. Crack propagation of beam 9

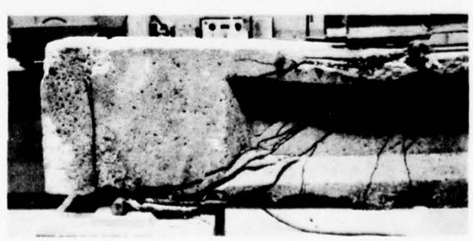
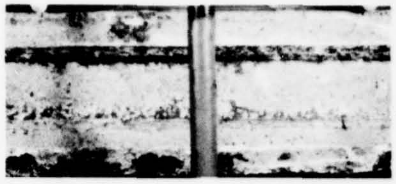
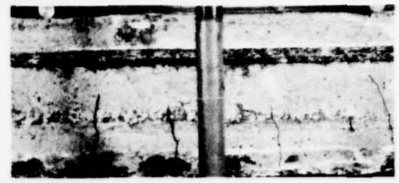


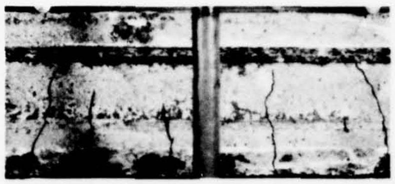
Photo A4. Failure condition of beam 9



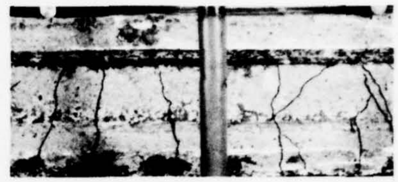
a. No load, 0.00-in. deflection



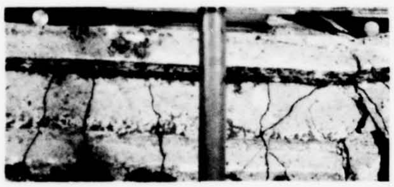
b. 45,000-lb load, 0.121-in. deflection



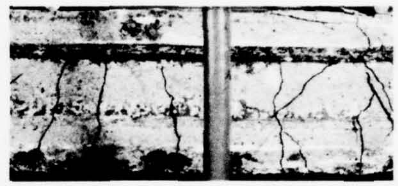
c. 55,000-lb load, 0.199-in. deflection



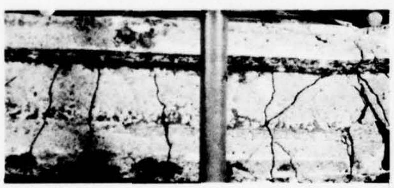
d. 60,000-lb load, 0.240-in. deflection



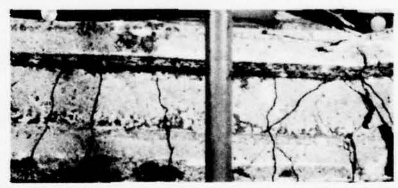
e. Failure, 61,713-lb load, 0.600-in. deflection



f. Post failure, 51,600-lb load, 0.800-in. deflection



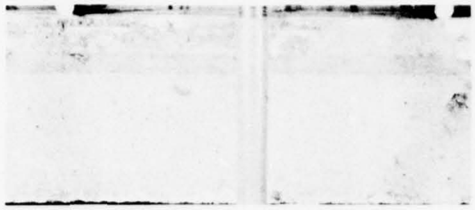
g. Post failure, 42,040-lb load, 1.000-in. deflection



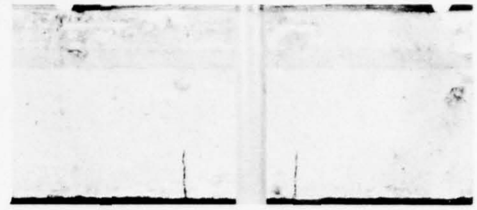
h. Post failure, 37,250-lb load, 2.000-in. deflection

Photo A5. Crack propagation of beam 13

Photo A6. Failure condition of beam 13

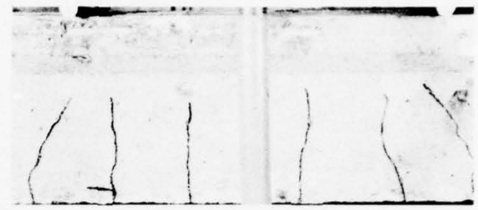


a. No load, 0.00-in. deflection

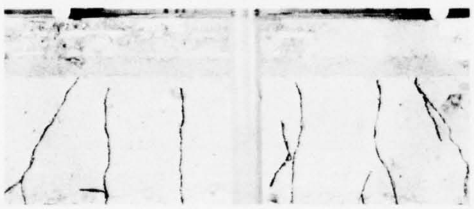


b. First crack, 40,000-lb load, 0.083-in. deflection

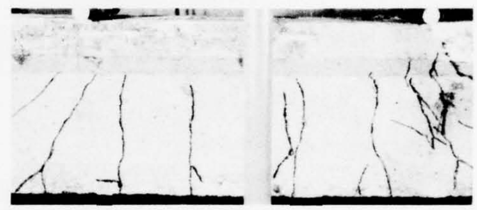
c. 50,000-lb load, 0.124-in. deflection



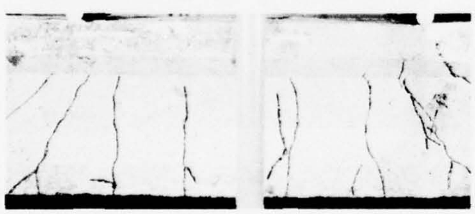
d. 60,000-lb load, 0.197-in. deflection



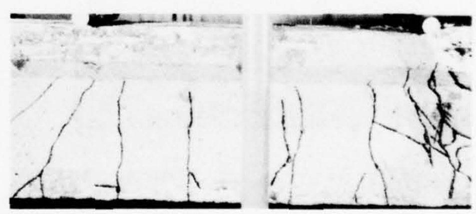
e. 66,240-lb load, 0.255-in. deflection



f. 69,364-lb load, 0.294-in. deflection



g. 72,779-lb load, 0.445-in. deflection



h. Failure, 74,828-lb load, 0.590-in. deflection

Photo A7. Crack propagation of beam 15

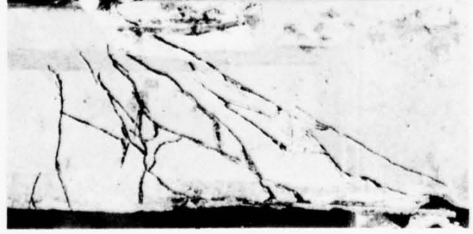
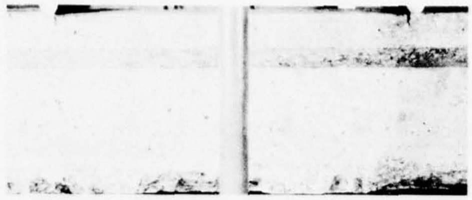
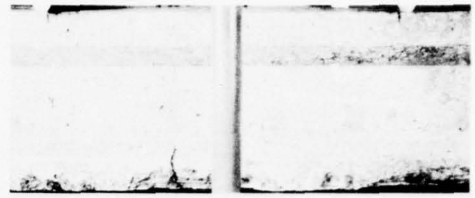


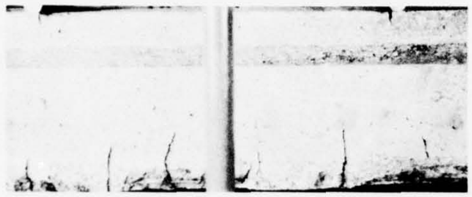
Photo A8. Failure condition of beam 15



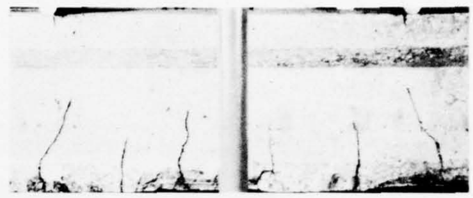
a. No load, 0.00-in. deflection



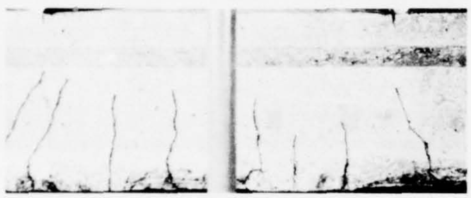
b. First crack, 45,000-lb load, 0.077-in. deflection



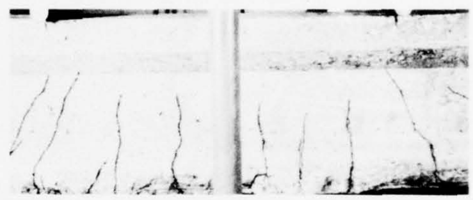
c. 60,000-lb load, 0.138-in. deflection



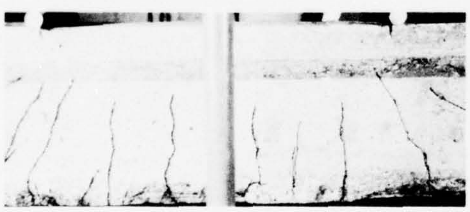
d. 65,000-lb load, 0.161-in. deflection



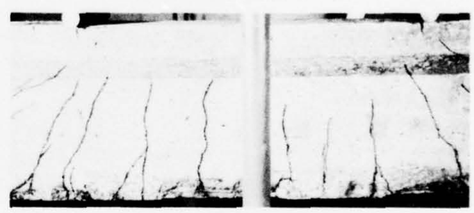
e. 75,000-lb load, 0.238-in. deflection



f. 82,000-lb load, 0.290-in. deflection



g. 85,000-lb load, 0.326-in. deflection



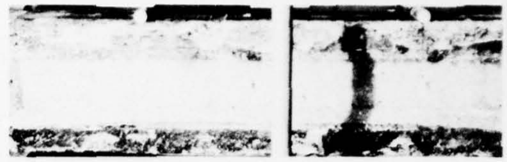
h. 93,000-lb load, 0.386-in. deflection

i. Failure, 93,954-lb load, deflection not known

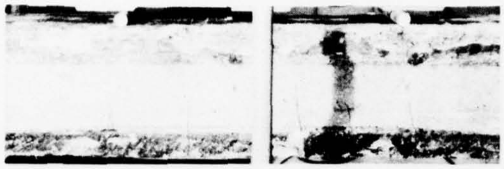
Photo A9. Crack propagation of beam 19

Photo A10. Failure condition of beam 19

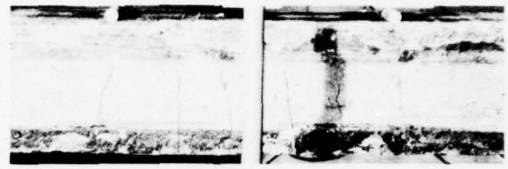
a. No load, 0.00-in. deflection



b. First crack, 36,600-lb load, 0.092-in. deflection

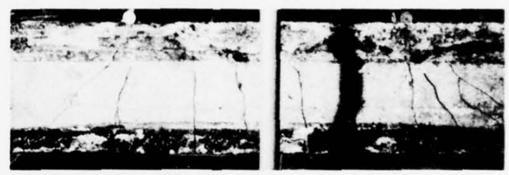


c. 50,000-lb load, 0.147-in. deflection

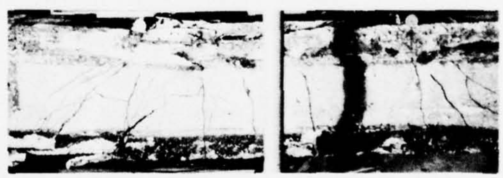


d. 65,000-lb load, 0.245-in. deflection

e. 70,000-lb load, 0.305-in. deflection



f. 70,000-lb load, 0.320-in. deflection



g. Failure, 75,000-lb load, 0.379-in. deflection

Photo A11. Crack propagation of beam 6

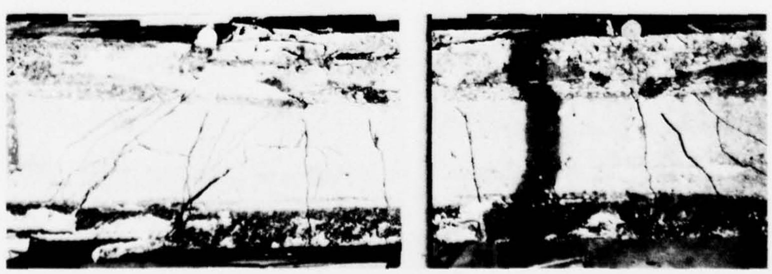
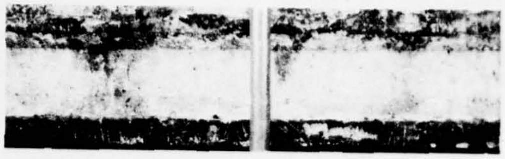
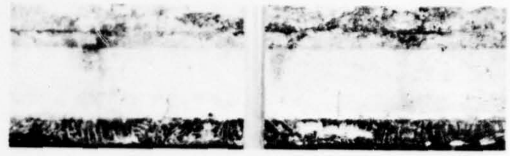


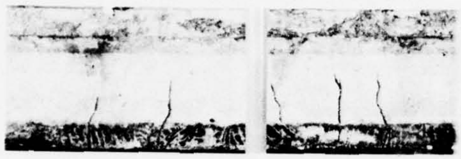
Photo A12. Failure condition of beam 6



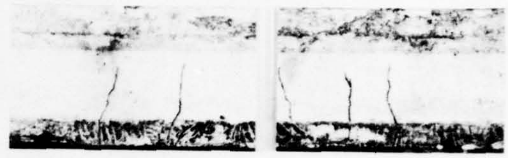
a. No load, 0.00-in. deflection



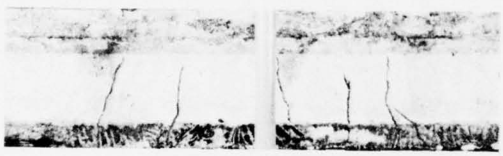
b. First crack, 48,870-lb load, 0.110-in. deflection



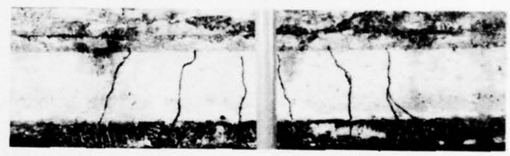
c. 55,000-lb load, 0.132-in. deflection



d. 60,000-lb load, 0.164-in. deflection

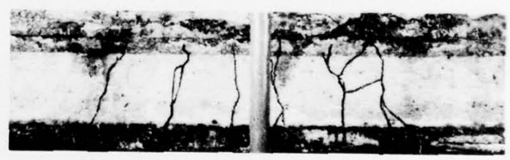


e. 65,000-lb load, 0.190-in. deflection



f. 75,000-lb load, 0.272-in. deflection

g. 80,000-lb load, 0.334-in. deflection



h. Failure, 87,800-lb load, 0.563-in. deflection

Photo A13. Crack propagation of beam 11

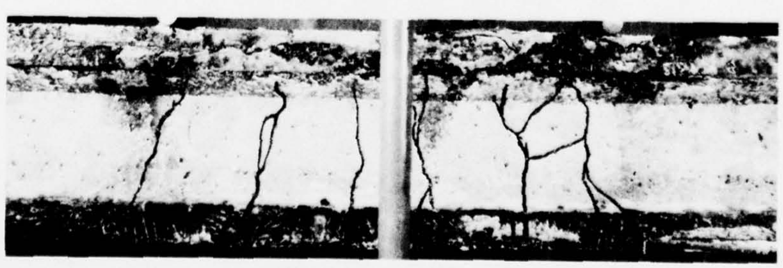
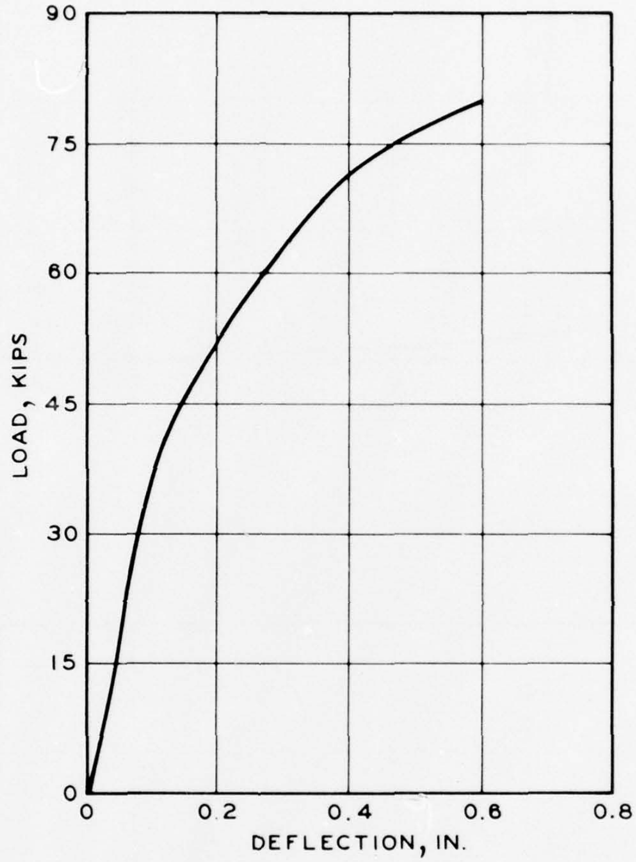
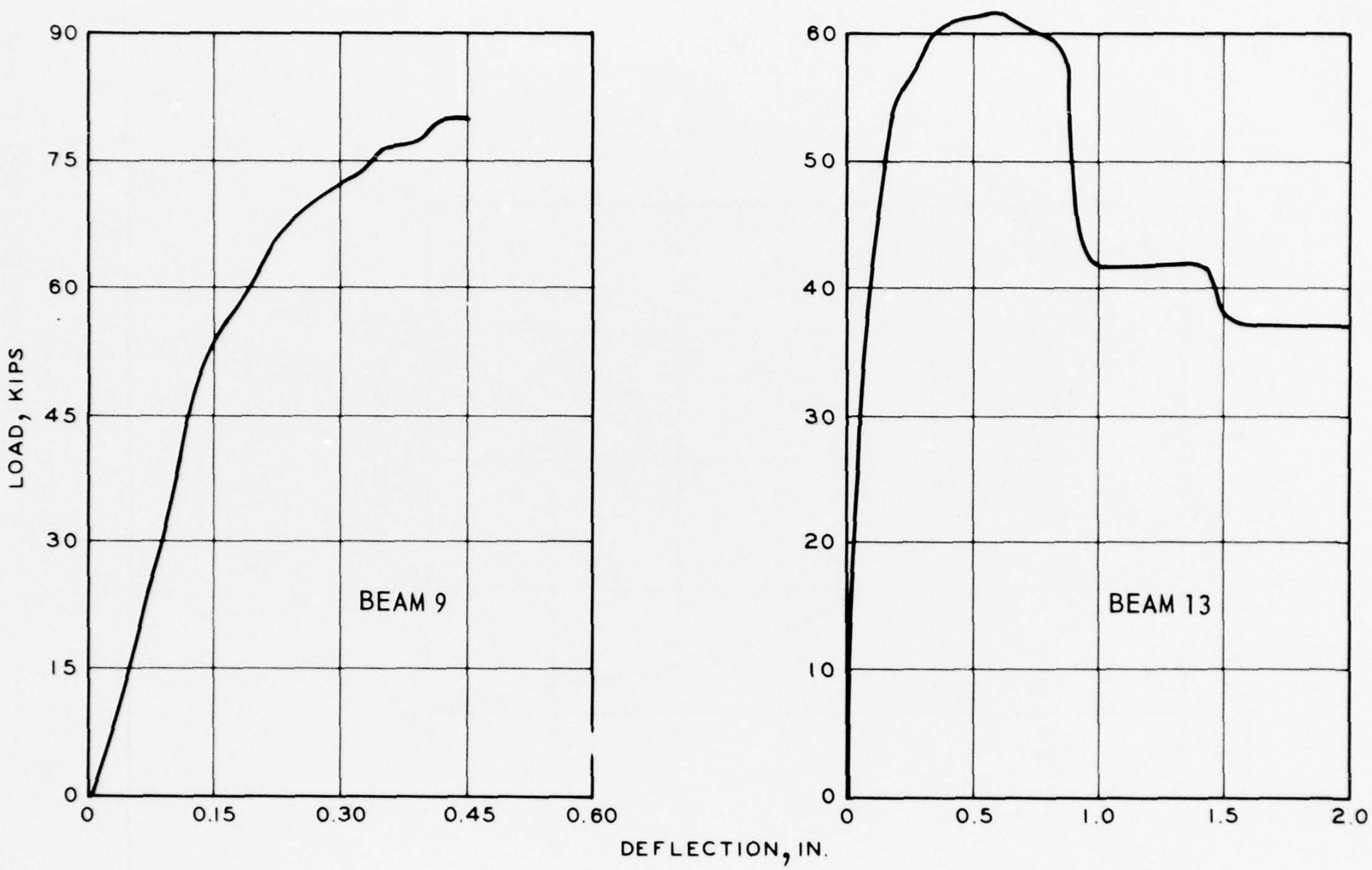


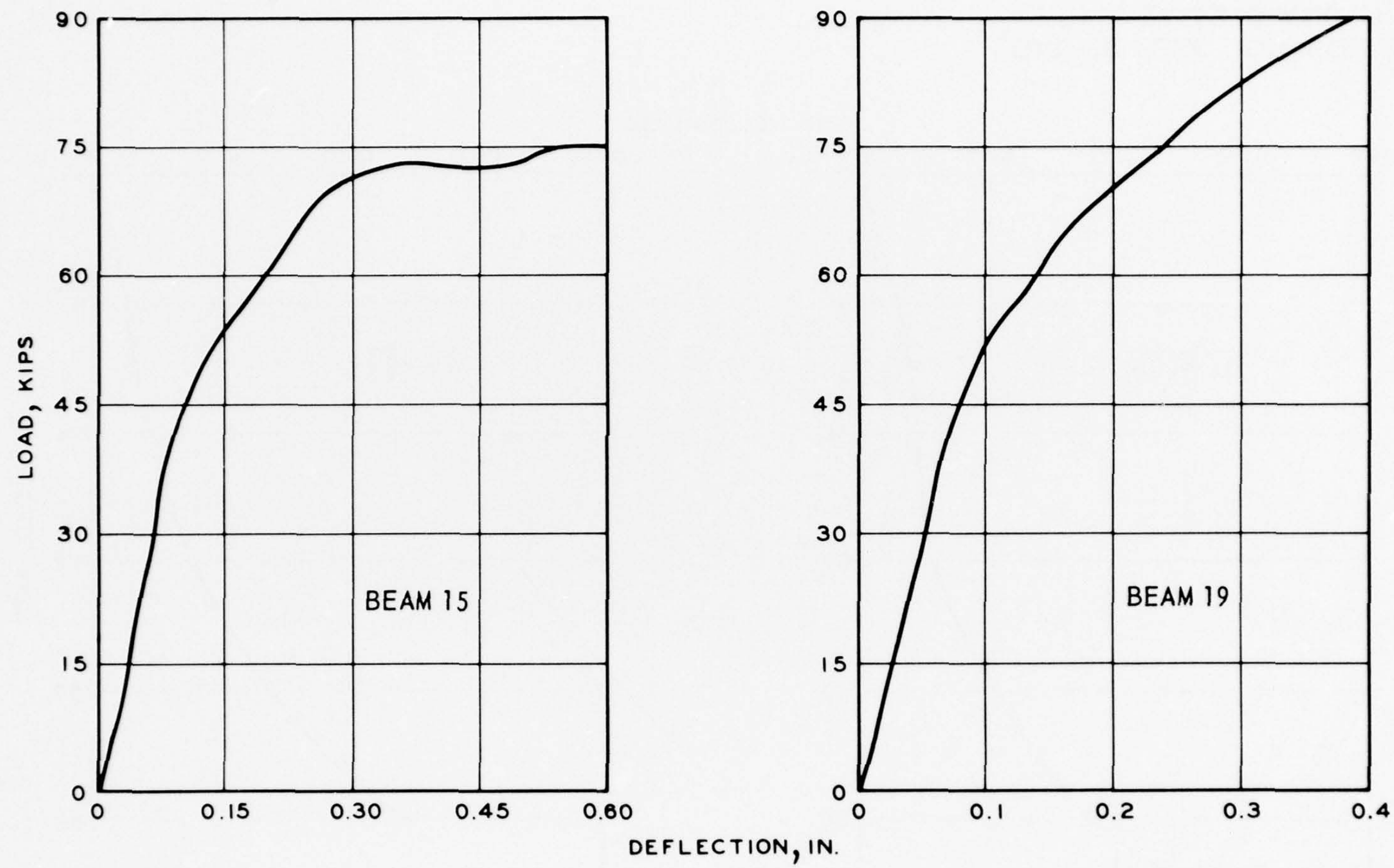
Photo A14. Failure condition of beam 11



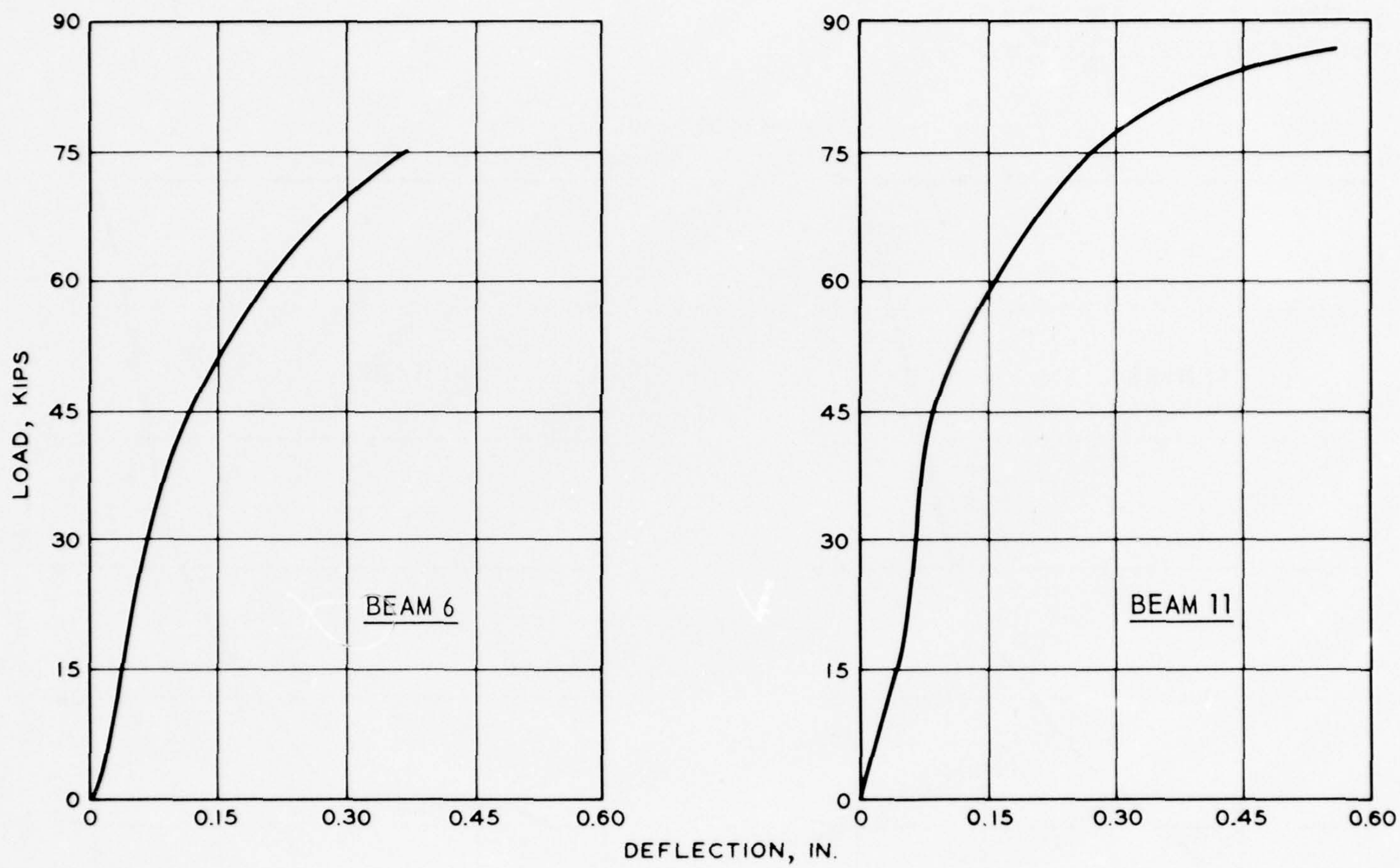
LOAD-DEFLECTION CURVE
FOR BEAM 3



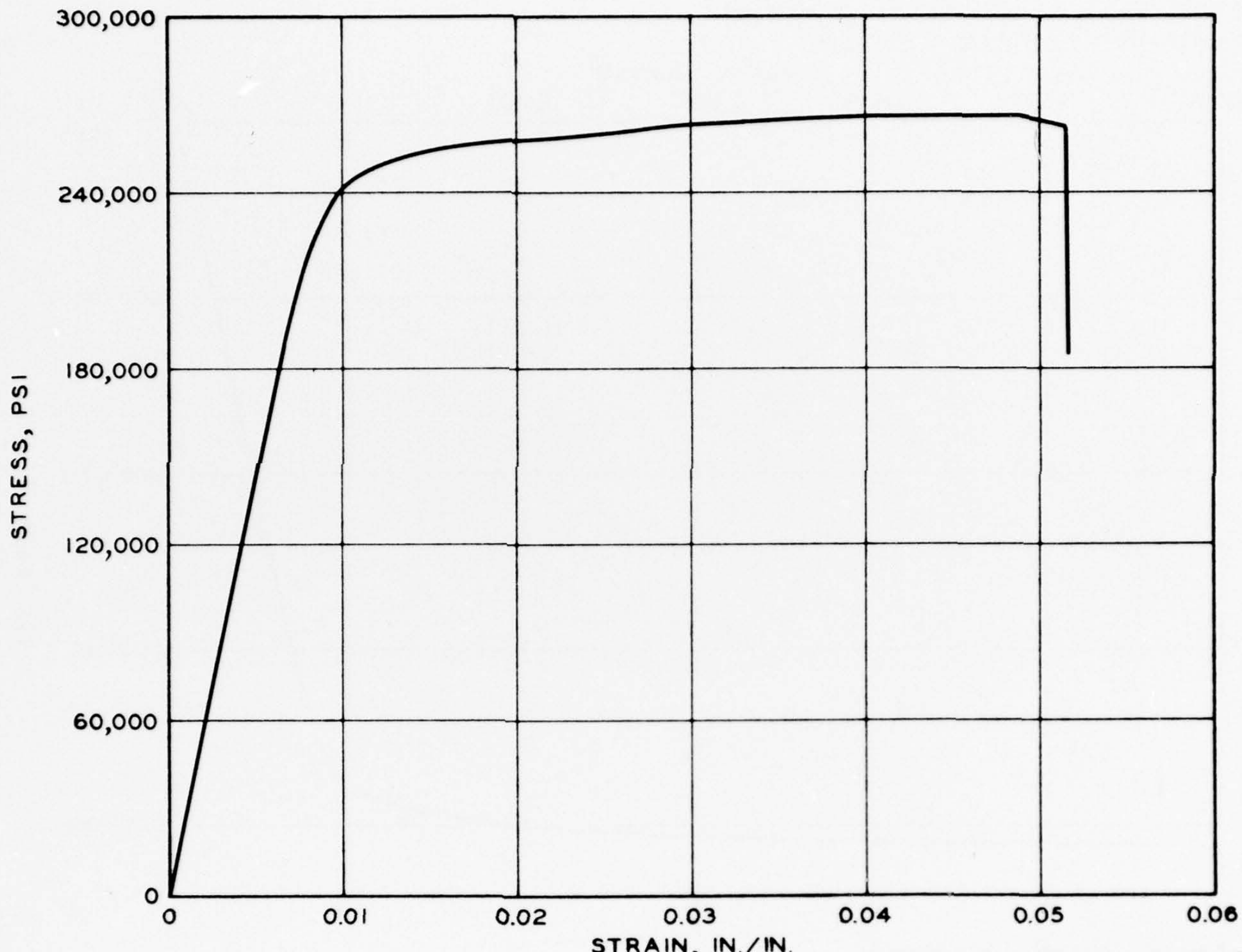
LOAD-DEFLECTION CURVES
FOR BEAMS 9 AND 13



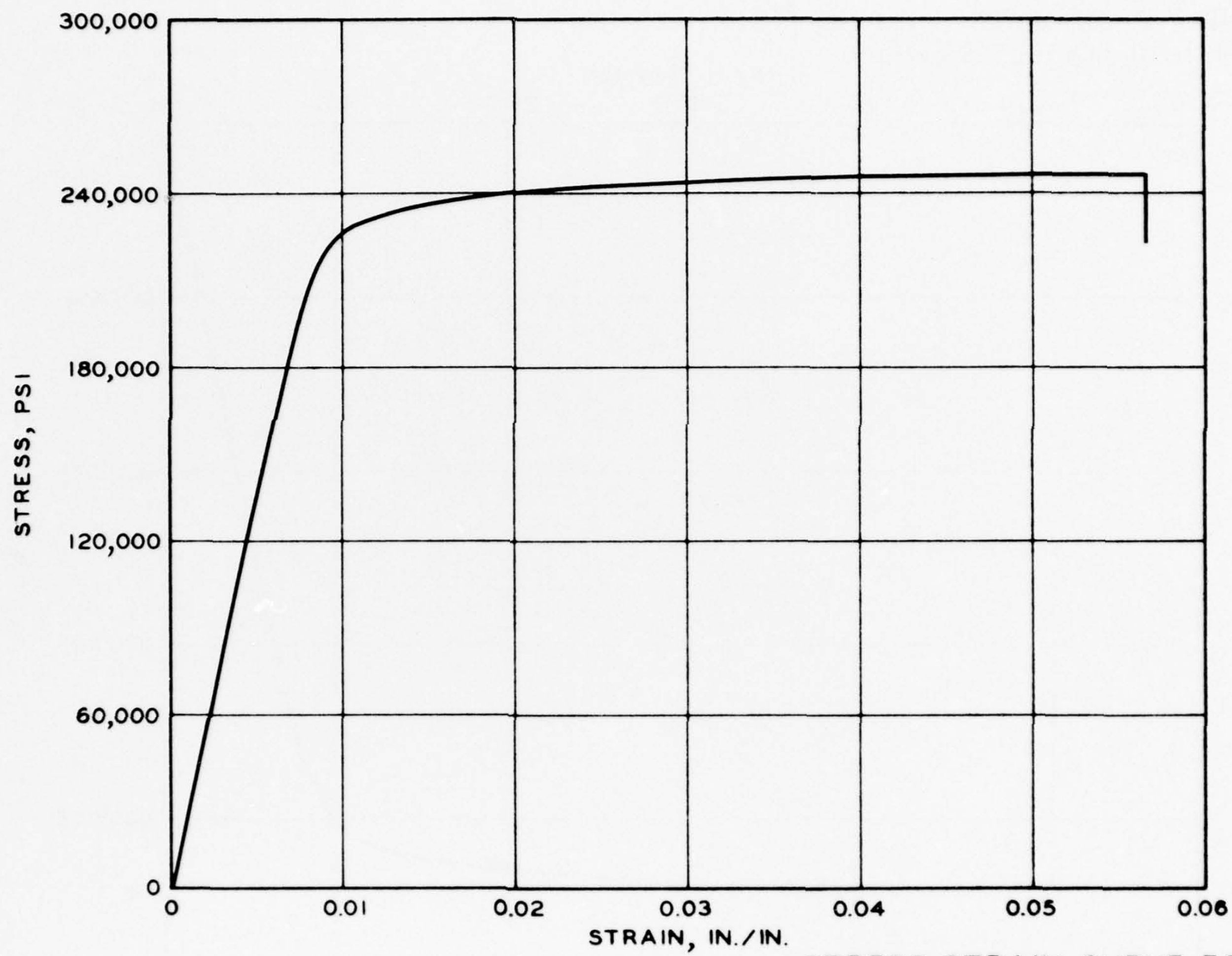
LOAD-DEFLECTION CURVES
FOR BEAMS 15 AND 19



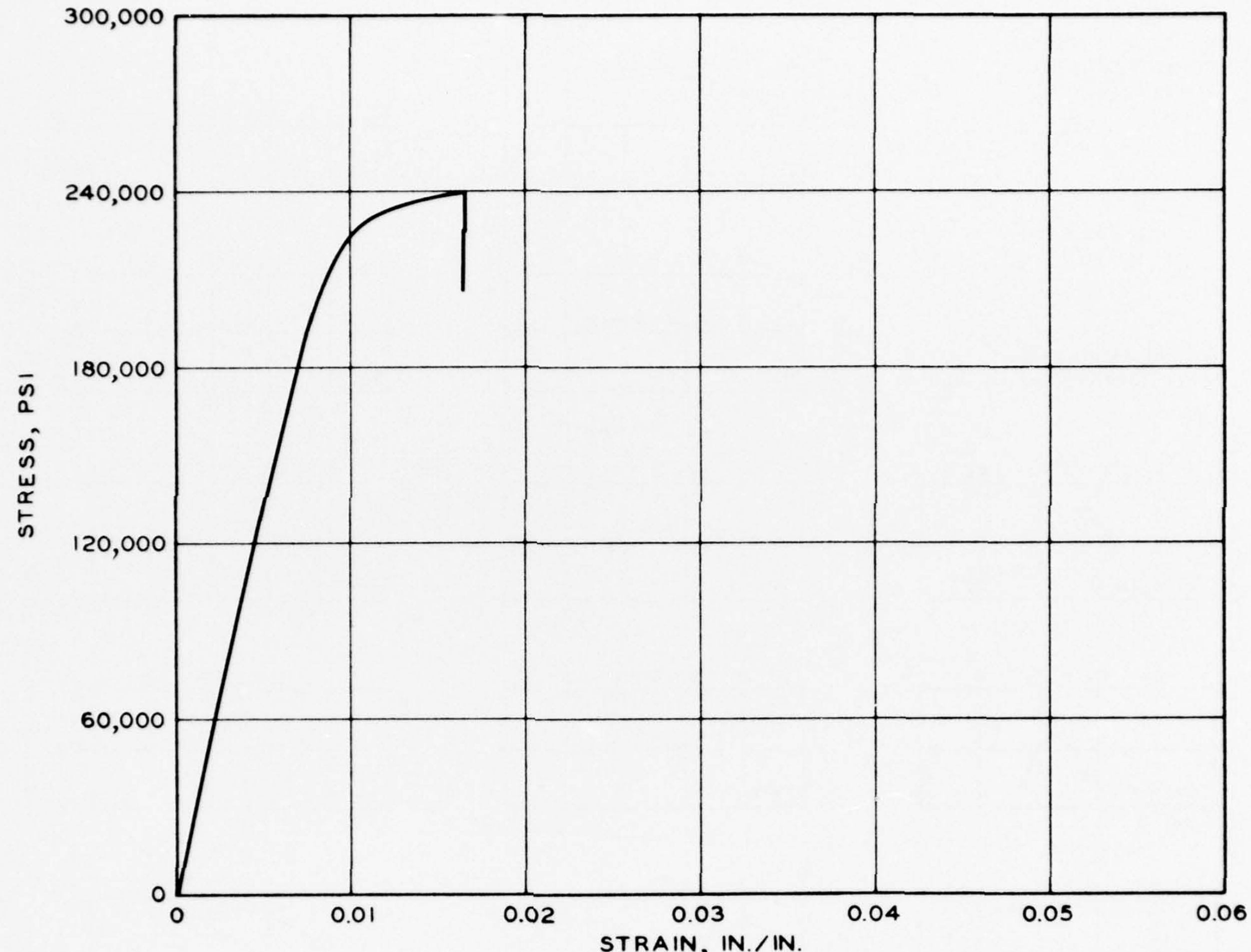
LOAD-DEFLECTION CURVES
FOR BEAMS 6 AND 11



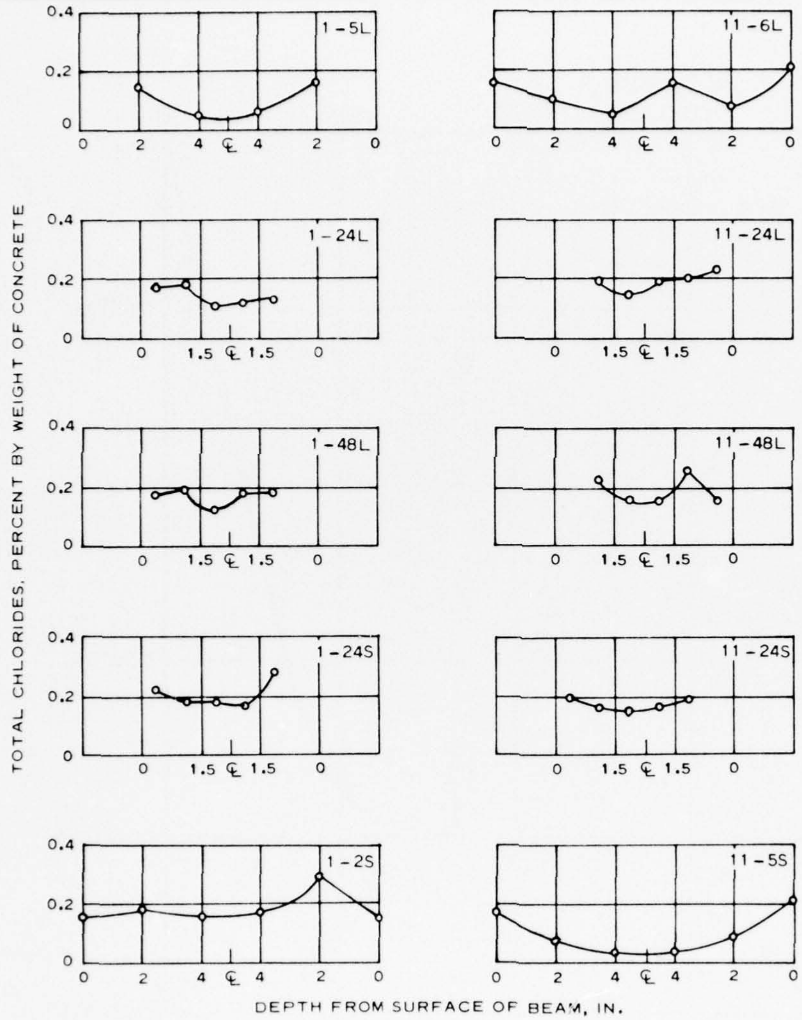
STRESS-STRAIN CURVE FOR
BEAM 1 - STRAND 2, MIDSPAN



STRESS-STRAIN CURVE FOR
BEAM 3 - STRAND 6, LANDWARD END



STRESS-STRAIN CURVE FOR
BEAM 13 - STRAND 4, LANDWARD END



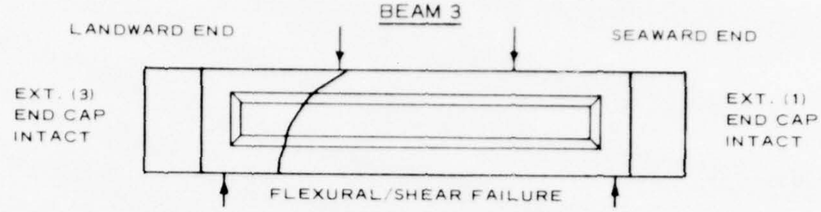
NOTE: 1-24L = BEAM 1, 24-IN. FROM LANDWARD END

TOTAL CHLORIDE CONTENT VERSUS DEPTH FROM SURFACE

PLATE A8

APPENDIX B: GRAPHIC SUMMARY OF BEAMS, END ANCHORAGES, AND MODES OF FAILURE OF THIS REPORT

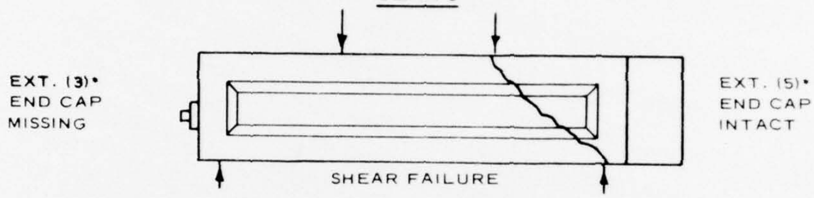
BEAM 3



EXTERNAL ANCHORAGE, BUSH-HAMMERED JOINT, NO REINFORCEMENT, AIR-ENTRAINED CONCRETE

EXTERNAL ANCHORAGE, NO JOINT TREATMENT, NO REINFORCEMENT, AIR-ENTRAINED CONCRETE

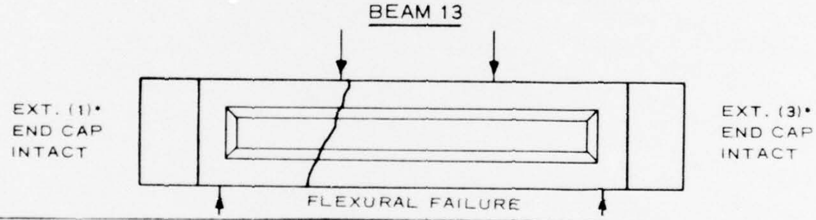
BEAM 9



EXTERNAL ANCHORAGE, BUSH-HAMMERED JOINT, NO REINFORCEMENT, AIR-ENTRAINED CONCRETE

EXTERNAL ANCHORAGE, JOINT TREATED WITH RETARDING AGENT, NO REINFORCEMENT, AIR-ENTRAINED CONCRETE

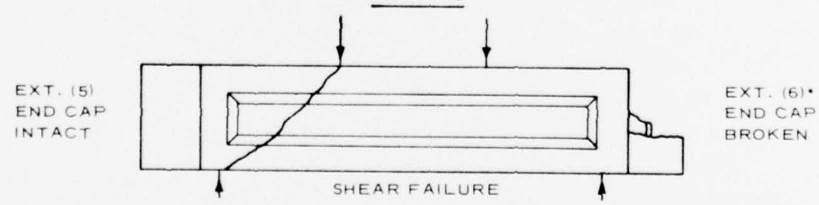
BEAM 13



EXTERNAL ANCHORAGE, NO JOINT TREATMENT, NO REINFORCEMENT, AIR-ENTRAINED CONCRETE

EXTERNAL ANCHORAGE, BUSH-HAMMERED JOINT, NO REINFORCEMENT, AIR-ENTRAINED CONCRETE

BEAM 15



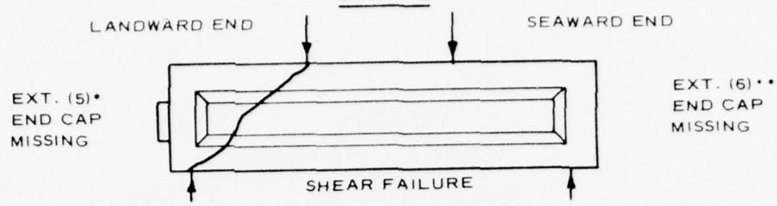
EXTERNAL ANCHORAGE, JOINT TREATED WITH RETARDING AGENT, NO REINFORCEMENT, AIR-ENTRAINED CONCRETE

EXTERNAL ANCHORAGE, CONCRETE BONDED WITH EPOXY ADHESIVE, NO REINFORCEMENT, AIR-ENTRAINED CONCRETE

NOTE: DATA COMPILED ARE FROM 5-YEAR REPORT.

* END PROTECTION HAD DEVELOPED A CRACK AT BOND LINE IN REPORTING OF 5-YEAR REPORT.

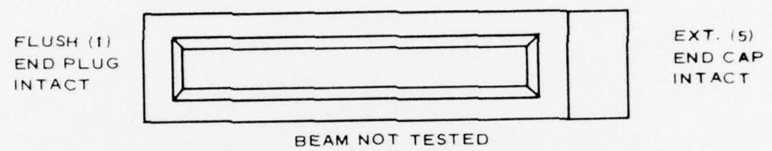
BEAM 19



EXTERNAL ANCHORAGE, JOINT TREATED WITH RETARDING AGENT, NO REINFORCEMENT, AIR-ENTRAINED CONCRETE

EXTERNAL ANCHORAGE, CONCRETE BONDED WITH EPOXY ADHESIVE, NO REINFORCEMENT, AIR-ENTRAINED CONCRETE

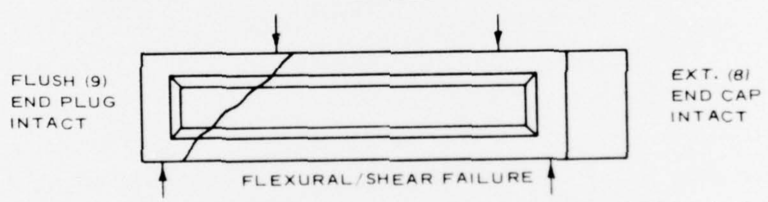
BEAM 1



FLUSH ANCHORAGE PLUG, NO JOINT TREATMENT, AIR-ENTRAINED CONCRETE, NO REINFORCEMENT

EXTERNAL ANCHORAGE, JOINT TREATED WITH RETARDING AGENT, AIR-ENTRAINED CONCRETE, *NO CAP* REINFORCEMENT

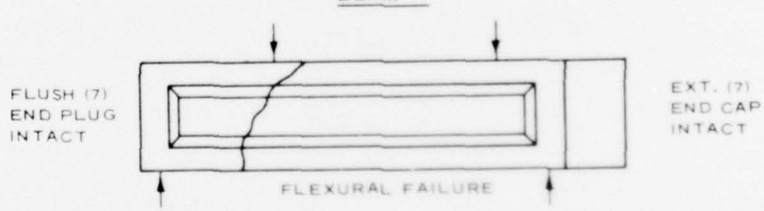
BEAM 6



FLUSH ANCHORAGE PLUG, NO JOINT TREATMENT, *SAND-CEMENT* MORTAR, NO REINFORCEMENT

EXTERNAL ANCHORAGE, EPOXY CONCRETE WITH REINFORCEMENT

BEAM 11



FLUSH ANCHORAGE PLUG, EPOXY CONCRETE WITHOUT REINFORCEMENT

EXTERNAL ANCHORAGE, EPOXY CONCRETE WITHOUT REINFORCEMENT

NOTE: DATA COMPILED ARE FROM 5-YEAR REPORT.

* END PROTECTION HAS BECOME LOOSE.

** END PROTECTION HAS BECOME DETACHED.

In accordance with ER 70-2-3, paragraph 6c(1)(b), dated 15 February 1973, a facsimile catalog card in Library of Congress format is reproduced below.

O'Neil, Edward F

Durability and behavior of prestressed concrete beams; Report 4: Posttensioned concrete beam investigation with laboratory tests from June 1961 to September 1975, by Edward F. O'Neil. Vicksburg, U. S. Army Engineer Waterways Experiment Station, 1977.

1 v. (various pagings) illus. 27 cm. (U. S. Waterways Experiment Station. Technical report 6-570, Report 4)

Prepared for Office, Chief of Engineers, U. S. Army, Washington, D. C.

Includes bibliography.

1. Concrete beams. 2. Concrete durability. 3. Concrete tests. 4. Concrete weathering. 5. Posttensioning. 6. Prestressed concrete. 7. Seawater corrosion. I. U. S. Army. Corps of Engineers. (Series: U. S. Waterways Experiment Station, Vicksburg, Miss. Technical report 6-570, Report 4)

TA7.W34 no.6-570 Report 4